Development of a Real-Time Monitoring/Dynamic Rating System for Overhead Lines

CONSULTANT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

EDM International Inc.

December 2003
500-04-003

Prepared By:

EDM International Inc.
4001 Automation Way
Fort Collins, CO 80525

Contract No. 500-98-034

Arun K Pandey, PhD

Prepared For:

California Energy Commission

David Chambers
Project Manager

Laurie ten Hope,
Program Area Lead
Energy Systems Integration

Terry Surles,
PIER Program Manager

Robert L. Therkelsen
Executive Director

Acknowledgements

This report was prepared by:

EDM International Inc.
4001 Automation Way
Fort Collins, CO 80525
www.edmlink.com

Principal Investigators:
Andrew Stewart
Arun Pandey
Neil Hurst

SUBCONTRACTORS:

Southwest Research Company
6220 Culebra Road
San Antonio, TX 78228

Principal Investigators:
Glenn Light
Richard Tennis

Power Line Systems, Inc.
918 University Bay Drive
Madison, Wisconsin 53705

Principal Investigators:
Eric Peyrot
Otto Lynch

EPRI
3412 Hillview Avenue
Palo Alto, California 94304

Principal Investigator:
Bernard Clairmont

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million per Year to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy System Integration.

What follows is the final report for the Development of a Real-Time Monitoring/Dynamic Rating System for Overhead Lines Project, Contract No. 500-98-034, conducted by EDM International Inc. The report is entitled "Development of a Real-Time Monitoring/Dynamic Rating System for Overhead Lines**".** This project contributes to the Energy Systems Integration (ESI) program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Table Of Contents

List of Figures

List of Tables

Executive Summary

As electrical demands increase, utilities are faced with upgrading their transmission systems by building new lines or when feasible increasing the allowable electrical loads on existing lines. Deregulation, competition, environmental pressures, and permitting issues are making it increasingly difficult to justify the construction of new transmission lines. Fortunately, most lines in North America have been designed using conservative criteria and therefore have significant excess capacity. Unfortunately, it is currently quite difficult, if not impossible for utilities to effectively utilize this excess capacity because of the lack of practical, easy-to-use technology to enable real-time monitoring and dynamic rating of lines.

The capacity of many existing lines is limited by conductor performance at high temperatures. Line capacity is limited to maintain the minimum ground clearances (the shortest allowable distance between the conductors and the terrain directly below the line) specified in codes such as California General Order 95 and the National Electrical Safety Code to avoid increases in sag with increased temperature, or annealing of the aluminum. This report presents the findings of a PIER project to develop sensor systems and software to allow an accurate real-time measurement of ground clearances along the length of lines and eliminate the use of very conservative assumptions by providing a real-time rating for the lines. Taking this approach of quantifying ground clearance/sag in real-time and providing a real-time rating for the lines allows utilization of many amps of hidden capacity.

Project Objectives

The overall objective for the project was to develop a system with sensors for monitoring ground clearances/sags in selected spans on a real-time basis coupled with software to model the clearances/sags in all spans that can provide a real-time rating for the line. The technical performance objectives of this project were to develop a practical, user-friendly and cost-effective transmission-line monitoring system with the flexibility and features needed to work with existing and state-of-the-art transmission systems. The goal for the line rating software design was to enable the system to be used by transmission system operators, including utilities and the Independent System Operator (ISO) for three purposes: 1) real-time monitoring/dynamic rating of lines, 2) studies to evaluate the performance of existing lines and to re-rate their capacity, and 3) monitoring the status of clearances/sags in "safety critical" areas.

Conclusions

The PIER project was successful in developing real-time sensors for ground clearance/sag measurements and rating software to provide real-time capacity for the monitored lines. Two sensor systems, a pulsed laser based (LDM) system and a machine vision based (Sagometer) system, were developed and tested. The developed sensor systems met or exceeded the performance standards set for the project. To focus the limited resources and because of the unique benefits offered by the Sagometer system, it was decided by the project team and approved by the Energy Commission to only develop a prototype for the Sagometer system. The key benefit offered by the Sagometer system was that it did not require any active component to be installed on the live wire. Prototype Sagometer sensor was fabricated and field tested on a line in Southern California Edison's system.

- The developed sensors can measure power-line clearances over a range of 20 to 100 feet with an accuracy of better than $\pm$ 2 inches. In fact, the resolution for the Sagometer sensor is 0.25 inch.
- The developed sensors are capable of real-time monitoring and dynamic rating of lines. In addition, historic clearance data gathered using these sensors could also be used for rating studies.
- Field installation of the sensor system can be completed and commissioned (debugged) in less than 4 hours. The Sagometer sensor system is designed to be installed without the need of taking an outage and the only component that gets attached to the live conductor is a completely passive target.
- The monitoring system is capable of reliable, low-maintenance operation (1 - 2 maintenance visits per year in conjunction with a utility's routine line patrol/inspection activities) in an outdoor environment.
- The monitoring system is capable of operation in remote sites during daylight and at night.
- The monitoring system is capable of ready integration of additional devices to the sensor system for making ancillary measurements such as wind speed and ambient temperature.
- The monitoring system is capable of autonomous remote reboot of hardware in the event of an operational or environmental anomaly that causes proper operation to cease.

The Sagometer system is designed to integrate with EPRI's Dynamic Thermal Circuit Rating software to obtain rating using the clearance data measured from the Sagometer. In addition, a rating module was developed around an existing sophisticated computer program (PLS-CADD) developed by Power Line Systems, Inc. (PLS) which enables the three-dimensional modeling of overhead lines and terrain for the purposes of designing new lines. The use of PLS-CADD software as the basis for the line rating module allows for monitoring of clearance/sag in any of the critical spans from the clearance/sag data from the span in which the Sagometer is installed. The real-time rating software has the capability to provide a steady state rating for the line along with an emergency rating for a user defined time period. The rating software can provide real-time rating based on either a clearance limit or a thermal limit depending on the limiting factor affecting the line being monitored.

Benefits to California

Development of a real-time rating system enables utilities to confidently operate many lines at electrical loads without exceeding National Electric Safety Code (NESC) specified clearances. A real-time rating system enables more efficient utilization of existing lines during normal operations, and increases the overall reliability of grid operations by enabling better utilization of alternative load paths during emergency operations. It is generally believed that a typical line will have 10 to 15% extra capacity over the static rating most of the time because of the conservative weather conditions assumed. In addition, through better utilization of existing lines, it results in significant environmental benefits by reducing the need to acquire right-of-way and construct additional transmission lines. A peripheral benefit of the developed system is that it could be used to monitor the status of critical spans in lines where safety is of particular concern, e.g. highway crossings, crossings over navigable waters, etc. Another benefit of the developed system is that it can be used to monitor high temperature operation of transmission lines and thereby estimating remaining life of the conductor which is known to be related to the amount of time a conductor is operated above a critical temperature.

Development of a real-time rating system provides several energy efficiency, cost, labor and environmental benefits for California. These benefits are listed below and are based on our discussions with people in the industry.

- A 2-5 percent increase in the power transfer capabilities of the existing grid.
- A 20-30 percent improvement in the transmission efficiency of existing lines that are limited by ground clearances.
- A 15-25 percent reduction in the need for acquisition and construction of additional ROW's and the associated environmental impacts.
- An improvement in system reliability enabled by improved knowledge of line capacity under normal and emergency conditions.
- Deferral of capital expenditures of $150-200 million for the construction of new transmission lines in the next 10 years.
- Long-term or permanent deferral of capital expenditures of $70-90 million per year for reconductoring projects.
- Short-term deferral of capital expenditures of $8-12 million per year for reconductoring projects.
- Stabilization or reduction in electricity rates enabled by more efficient use of existing overhead facilities and deferral of capital expenditures for the construction of new facilities.

Commercialization Potential

Both the developed sensor systems and rating software have excellent commercialization potential. The Sagometer sensor and line rating software are both ready for commercialization. Because this project has been running in parallel with other EPRI sponsored projects, multiple Sagometer systems have been deployed at utilities across the USA and Canada as part of EPRI sponsored Tailored Collaboration projects for long term performance evaluation. Several utilities in the US and two in Canada have approximately 30 Sagometer systems currently installed. The Sagometer installed cost target for the project was $45,000 and in fact, it came in approximately thirty percent cheaper than the target. Installation of the Sagometer system does not require a line outage offering significant additional cost savings.

The Laser Distance Measurement sensor pre-prototype also has commercialization potential but its packaging requires further development.

Recommendations

The following recommendations are offered to further enhance the real-time rating capabilities of the developed sensor and software system, and to make it widely acceptable by utilities:

- Further evaluation of the Sagometer sensor system on lines in California is needed to demonstrate the capabilities of the developed sensor system and to make it acceptable for dynamic rating of lines. This will help familiarize the California utilities with the system and also help identify any California utility specific needs for integration.

- Develop a line rating kit that incorporates a complete set of tools (sensors, analytical procedures, and software) for studying the behavior of transmission lines under "real-world" operating conditions for a relatively short period thereby enabling optimization of static ratings. This tool could be used as a study tool and be moved from one line to another with relative ease.
- Conduct line behavior research and develop procedures/guidelines for deploying sensor technology to optimize ratings for individual lines, paths, groups of lines, systems. Understanding the behavior of lines, paths and systems will help identify the critical lines that need to be monitored in order to obtain optimized ratings for the entire system.
- Develop procedures and guidelines for "seamless" real-time rating data integration into control room. For rating data to be used in real-time it needs to be integrated into the utilities control room and California Independent Systems Operator's (CAISO) control room.
- Perform economic benefit analysis studies of using real-time rating technology to quantify the benefits of using these new sensor technologies.
- Further develop the packaging for the pulsed laser based (LDM) sensor to enable it to be offered as an alternative sensor to the Sagometer. The LDM sensor could be beneficial in certain situations. One of the advantages of the LDM sensor is that it does not require any field calibration and provides a direct measurement of ground clearance.

Abstract

The stated capacity of many existing lines is based on very conservative assumptions of weather conditions to maintain the minimum ground clearances specified in safety codes at a given electric load. The overall objective for this project was to develop a system with sensors and software to monitor ground clearance in real-time and provide dynamic ratings for the monitored line thereby minimizing the need for the conservative assumptions. Development of such a sensor system would allow safe utilization of the hidden capacity of existing lines providing extensive economic and environmental benefits.

The PIER project leveraged some EPRI sponsored work and enabled the successful development of sensors capable of making real-time ground clearance/sag measurements and rating software to provide real-time capacity for the monitored lines. The developed sensor systems met or exceeded the proposed targets for ease of installation, accuracy, reliability and cost. Two sensor systems, a machine vision based system and a laser distance measurement (LDM) system, were developed and tested. The machine vision based system, which became known as the Sagometer, was fully developed while the LDM based-system was, due to budget limitations, only developed to the functional prototype stage. The Sagometer system was successfully field tested on a line from Southern California Edison's system. The Sagometer system integrates with EPRI's Dynamic Thermal Circuit Rating software and the newly developed PLS-CADD line rating module which can be used for studies to enhance the ratings of lines and to provide real-time rating using the measured clearance data. The developed real-time rating software has the capability to provide a steady state rating for the line along with an emergency rating for a user defined time period.

Both the developed sensor systems and rating software have excellent commercialization potential. The Sagometer sensor and the line rating software are both ready for commercialization. Several utilities in the US and Canada have already installed approximately 30 Sagometer systems as part of EPRI sponsored Tailored Collaboration projects.

1.0 Introduction

As electrical demands increase, utilities are faced with upgrading their transmission systems by building new lines or when feasible increasing the allowable loads on existing lines. Deregulation, competition, environmental pressures, and permitting issues are making it increasingly difficult to construct new transmission lines. Thus, increasing the allowable electrical loads on existing lines is an attractive option. For the cases where substation equipment is adequate, the electrical capacity of overhead lines is controlled by a variety of factors including line length, conductor type, phase spacing, insulation, and ambient conditions such as temperature, wind speed and solar radiation. Fortunately, most lines in North America have been designed using conservative criteria and therefore have significant excess capacity. Unfortunately, it is currently quite difficult, if not impossible for utilities to effectively utilize this excess capacity because of the lack of practical, easy-to-use technology to enable real-time monitoring and dynamic rating of lines.

The capacity of many existing lines is limited by conductor performance at high temperatures, i.e., exceeding the minimum ground clearances (the shortest allowable distance between the conductors and the terrain directly below the line) specified in codes such as California General Order 95 and the National Electrical Safety Code because of increases in sag with increased temperature, or annealing of the aluminum. Because utilities do not have an accurate real-time measure of ground clearances along the length of lines, they are constrained to use very conservative assumptions so as not to violate safety code requirements. In taking this approach many amps of capacity that could be utilized if ground clearance/sag could be quantified on a real-time basis are lost.

This report presents the findings of a PIER project to develop a system with sensors for monitoring ground clearances/sags in selected spans on a real-time basis coupled with software to model the clearances/sags in all spans. Development of a real-time monitoring system would enable utilities to confidently operate many lines at higher temperatures without exceeding code specified clearances. Such a system would enable more efficient utilization of existing lines during normal operations, and increase the overall reliability of grid operations by enabling better utilization of alternative load paths during emergency operations. In addition, through better utilization of existing lines, such a system will result in significant environmental benefits by reducing the need to acquire right of way and construct additional transmission lines. A peripheral benefit is that such a system could be used to monitor the status of critical spans in lines where safety is of particular concern, e.g. highway crossings, crossings over navigable waters, etc.

Monitoring of conductor ground clearance/sag could also be used to determine conductor life by tracking high temperature operations of the conductor which is directly related to clearance/sag. Tacking conductor operation below a set clearance limit is probably one of the best approach for tracking high temperature operations as it takes into account all the effect of the weather and the loading.

1.1. Background

The amount of power (amperage) that can be transmitted through a line is called its *rating*. The concept of a line's rating is further refined to include a *steady-state rating* (that amount of power that could be transmitted forever if ambient conditions around the line remained constant), and *emergency rating* (the amount of power that could be transmitted for a defined length of time).

There are several existing methods for rating lines. These methods are briefly described below.

Static Rating – Ambient conditions are assumed, and conductor temperature is calculated. From conductor temperature, the conductor sag is calculated, which is the governing criterion for line rating. For safety reasons, very conservative ambient conditions must be assumed, resulting in much lower ratings than the true power capacity of the line. Even then, there is the definite possibility of clearance violations since the assumptions are not conservative enough some small fraction of the time. Also, it is well documented that sag calculations for Aluminum Conductor Steel Reinforced (ACSR) conductors at elevated temperatures are significantly wrong in the un-conservative direction (i.e. sags are larger than predictions).

Semi-Dynamic Rating – Ambient conditions are measured in real-time, conductor temperature is calculated, conductor sag is calculated from conductor temperature. In this case, the ambient conditions are better known in real-time from strategically placed weather stations, however, the ambient conditions at the measuring sites may be different than those experienced by the line as a whole. Also, any errors in sag calculations (such as those for ACSR conductors at elevated temperatures) still exist.

Early Dynamic Rating Schemes – The temperature of a conductor is measured by a device such as a power donut. This data is transmitted to a ground-based station by means of an internal radio transmitter, and is then transmitted to a control center via cell phone, spread spectrum radio, or the equivalent. The conductor sag is calculated from the conductor temperature. One drawback is that the temperature is measured only at one point, and this may not represent the average temperature of the line. It is known that the temperature of a conductor can vary significantly along its length, even within a single span. Also, any errors in sag calculations (such as those for ACSR conductors at elevated temperatures) still exist.

Present Dynamic Rating Methods – There are two commercially available systems for monitoring ground clearance in real-time for dynamic rating purposes. One system consists of a load cell placed in series with a conductor at a dead-end structure to measure tension, and the other consists of a ground based unit which transmits an acoustic signal up to the conductor, and measures the time for its echo to arrive back to a receiver, and calculates the distance based upon the speed of sound. The first system measures tension, not sag or ground clearance, and it must be installed at a dead-end structure. The tension is used to calculate the ground clearance down line of the dead-end. This requires the use of ruling span assumptions, and is not a direct measurement of ground clearance. Also, because the load cell is placed in series with the conductor, the line must be taken out of service for installation, or live-line installation techniques must be used. The system based on acoustics requires the use of a relatively large ground-based unit.

EDM recognized the need for technology for monitoring conductor tension, sag and clearance, and in the mid-1990's began conducting research to develop an inspection device that could be quickly connected to an overhead conductor to measure tension and sag. This research led to development of a patented process for measuring conductor tension and was the catalyst for EDM to begin examining the feasibility of developing other sensor systems that could be connected to overhead lines for the purpose of performing the long-term, real-time monitoring of conductor ground clearances/sags which could be used as the basis for a real-time dynamic rating system. EDM's preliminary investigations culminated in the award of an EPRI contract in 1997 to examine the feasibility of using a variety of different sensor technologies for this purpose.[1] This EPRI research proved the feasibility of several concepts and initiated an investigation into the capabilities of others. The results of the EPRI-sponsored research were utilized as the foundation for this project.

The ground clearance/sag sensor systems were designed to interface with EPRI's existing line rating software, Dynamic Thermal Circuit Rating (DTCR). DTCR provides a rating from the clearance/sag measurements and weather parameters. To effectively use the sensor system to monitor an entire line and to gain the ability to install the sensor system anywhere on the line besides the critical span, line monitoring and rating software was necessary that also included three-dimensional modeling of overhead lines and terrain. A line rating and monitoring software was constructed around an existing sophisticated computer program (PLS-CADD) developed by Power Line Systems, Inc. (PLS) for the purposes of designing new lines. The availability of this three-dimensional modeling capability represented a very significant cost savings to the project as the complex analysis engine used for the design software could be used for the line rating software.

The aforementioned availability of the EPRI-sponsored sensor feasibility study results and the PLS line design model, dramatically increased the likelihood of success of this project.

1.2. Project Objectives

The overall goal of this project was to increase the efficient use of overhead transmission lines by developing a monitoring system which provides instantaneous information on the status of the lines' power-carrying capacity and safety code compliance related to power-line ground clearance. Using this information, electric grid operators can increase power transfers if lines have extra capacity or reduce current flow if lines are sagging and too close to the ground or to undergrowth.

The overall technical performance objectives of this project were to develop a practical, user-friendly and cost-effective transmission-line monitoring system with the flexibility and features needed to work with existing and state-of-the-art transmission systems. The system includes: 1) a monitoring system with practical installation, maintenance and operating parameters for overhead-line application; and 2) a data analysis and reporting system for conducting capacity-rating analyses and for real-time monitoring of line sag and ground-clearance conditions by transmission system operators, including utilities and the Independent System Operator (ISO).

The specific technical performance objectives, which were used to measure the project's success, are:

- The sensors can measure power-line clearances over a range of 20 to 100 feet with an accuracy of better than $\pm$ 2 inches.
- The sensors are capable of real-time monitoring and dynamic rating.
- Field installation of the sensor system can be completed and commissioned (debugged) in less than 6 hours.

- The monitoring system is capable of reliable, low-maintenance operation (1 - 2 maintenance visits per year in conjunction with a utility's routine line patrol/inspection activities) in an outdoor environment.
- The monitoring system is capable of operation in remote sites during daylight and at night.
- The monitoring system is capable of reliable operation in temperatures ranging from –10°F to +120°F.
- The monitoring system is capable of ready integration of additional devices to the sensor system for making ancillary measurements such as wind speed and ambient temperature.
- The monitoring system is capable of autonomous remote reboot of hardware in the event of an operational or environmental anomaly that causes proper operation to cease.

1.3. Project Team

The Project Team consists of experts with complementary backgrounds related to sensor technology, software for modeling overhead lines, research and development and project management. The following organizations were part of the Project Team:

- EDM International, Inc. (EDM)
  (Fort Collins, Colorado)
- Southwest Research Institute, Inc. (SwRI)
  (San Antonio, Texas)
- Power Line Systems, Inc. (PLS)
  (Madison, Wisconsin)
- Electric Power Research Institute (EPRI)
  (Palo Alto, California)

EDM was the Project Team leader with active participation from all members of the Project Team. EDM has a high level of expertise in projects related to the design, operation, monitoring and maintenance of overhead lines. EDM had the overall responsibility for the prototype sensor system development and fabrication, integration of the sensor and rating software, field trails and commercialization efforts.

SwRI is one of the original and largest independent not-for-profit applied research and development organizations in the United States. SwRI had the primary responsibility for the laser and machine vision-based sensor research and development and for sensor packaging, power supply, data storage and data communication.

PLS is the nation's leading developer of software for the design and analysis of overhead lines. PLS had the primary responsibility for the research and development on the line monitoring/dynamic rating software.

EPRI is the largest not-for-profit organization managing and conducting research and development for the electric utility industry. EPRI acted as a co-sponsor for the project and also conducted the laboratory evaluation of sensor performance under electric and magnetic fields.

1.4. Report Organization

This report is organized as follows:

Section 1.0	Introduction
Section 2.0	Project Approach
Section 3.0	Project Outcomes
Section 4.0	Conclusions and Recommendations
Section 5.0	References

There are two appendices.

Appendix A	Functional Specifications for Sensor System
Appendix B	Line Rating Software Acceptance Test Plan

2.0 Project Approach

The overall goal for the project was to conduct research and development necessary to produce a system for real-time conductor ground clearance/sag monitoring and dynamic rating of lines. The goal was to develop a system that incorporates sensors for measuring conductor ground clearances/sags in selected spans on a real-time basis and to develop software that will utilize the sensor measurements to provide a robust real-time dynamic rating system.

The basic concept of the sensors for measuring ground clearance/sag is illustrated in Figure 2-1. The sensor can either

A. be attached to the wire and look down at the ground, or

B. be attached to one of the structures supporting the conductor or any other structure and look towards the span to be monitored.

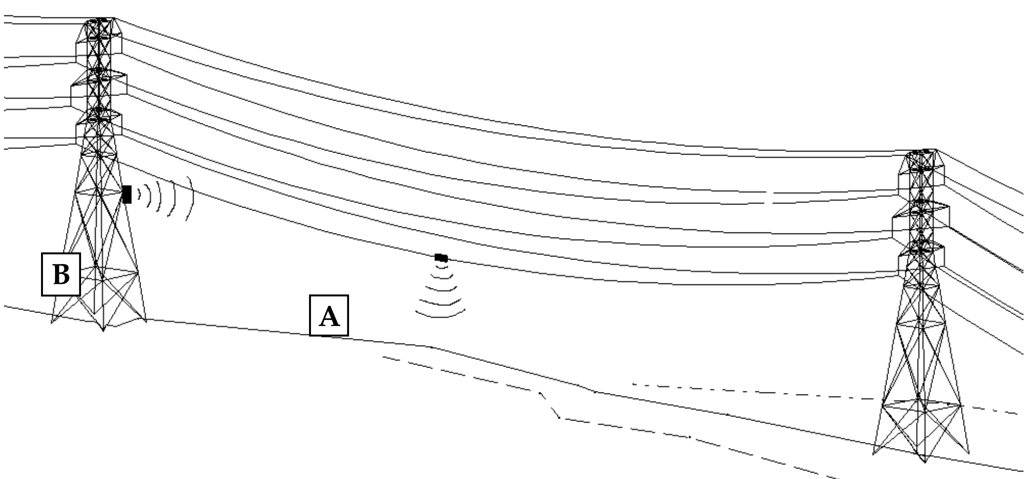


Figure 2-1 Schematic Showing Two Possible Attachment Locations For Conductor Ground Clearance/Sag Monitoring Sensors

Three sensors were identified as being promising for real-time conductor ground clearance/sag monitoring application in a recent EPRI-sponsored feasibility study. The development of all three sensors was planned in this project to increase the likelihood of success and to provide a range of sensors that would be appropriate for different line operating constraints. The basic concepts for the three potential sensors are as follows:

> <u>Microwave:</u> A small, low-cost microwave emitter/receiver would be placed on the conductor at mid-span or other location to be monitored. The emitter/receiver would send signals towards the ground, receive reflected signals, and process the signals to determine the distance from the ground to the conductor.
>
> <u>Pulsed Laser – Laser Distance Measurement (LDM):</u> A small, low-cost pulsed laser emitter/receiver would be placed on the conductor at mid-span or other location to be monitored. The emitter/receiver would send signals towards the ground, receive reflected signals, and process the signals to determine the distance from the ground to the conductor.
>
> <u>Machine Vision - Point Source to Tower Measurement (PSTM):</u> A small machine vision system mounted on one of the transmission line structures would monitor the conductor itself or a small point source (active target with inductively powered light emitting diodes or a passive target) mounted at a set distance from the vision system. The image would be analyzed using machine vision analysis software to determine changes in sags and clearances. The use of a passive target without any point source became more appealing as the research progressed and led to the system being called a "Video Sagometer" and later just "Sagometer"

As the early stages of the project progressed, it became increasingly apparent that the Project Team will be successful in developing practical, reliable and cost-effective sensors. In fact, it appeared that both the efforts based on the machine vision and laser-based sensors would be successful and would lead to the development of viable solutions for monitoring conductor ground clearance/sag. In contrast, the Project Team discovered early on that there were some limitations of the microwave technology that without substantial R&D investment may limit its practicality and reliability. While some of the identified shortcomings with the microwave technology could be overcome, the Project Team felt it would be more effective use of the project resources to focus on the machine vision and laser-based sensor developments and to discontinue pursuit of the microwave development. This change was approved by the Energy Commission and enabled more efficient and effective use of the available resources by focusing on the more promising sensor technologies.

The goal for the line rating software design was to enable the system to be used for three purposes: 1) real-time monitoring/dynamic rating of lines, 2) studies to evaluate the performance of existing lines and to re-rate their capacity, and 3) monitoring the status of clearances/sags in "safety critical" areas. The line rating software was built around an existing software suit for three dimensional modeling of overhead lines and terrain that is currently being used for designing new lines.

The integrated sensor and software system also provides the ability to access and analyze measurements of ancillary quantities such as wind speed, ambient temperature, conductor temperature and electrical load to enable the system to be used not only to monitor clearances/sags on a real-time basis, but to also examine current conditions and warn operators that clearance violations may occur in a user defined period of time if electrical loads or ambient conditions do not change.

The research and development effort towards development of the sensor and software system focused on the following activities:

- Assess the viability of, optimize and design one or more of the three potential sensor systems (i.e., microwave, pulsed laser, and machine vision - point source to tower measurement sensors).
- Develop a field worthy deployment system (including power supply, communications, and optional ancillary measurement capabilities (e.g. conductor temperature, wind speed, electrical load) for the most promising sensors.
- Develop the functional requirements for the software for real-time monitoring/rating of lines.
- Develop the software for real-time monitoring and dynamic rating of lines.
- Integrate the sensor technology with the software.
- Install and use the system on a trial basis on selected lines in California.
- Refine and finalize the system based on the results of the field trials.
- Document the research and development effort and prepare a commercialization plan.

2.1. Technical Advisory Group

A technical advisory group (TAG) was established at the beginning of the project to review, comment and suggest improvements to the project's technical and performance objectives, system specifications and designs, test plans and test results. The assembled TAG consisted of the project team, transmission engineering, planning and operations employees from California electric utilities, a member of the California Independent System Operator (ISO) Maintenance Coordination Committee, and Energy Commission contract manger. Members of the TAG and their organization are listed in Table 2-1.

A kick-off meeting was held at the start of the project. In addition, meetings of the technical advisory group were held throughout the duration of the project and a final project meeting is scheduled at the completion of the project.

Table 2-1 List of TAG Members and their Organizations

ROLE	NAME	ORGANIZATION
Energy Commission Contract Manager	Chambers, David	California Energy Commission
TAG	Burnham, Mark	Pacific Gas & Electric
TAG	Butler, Gilbert	Sacramento Municipal Utility District
TAG	Lyon, Deane	California ISO
TAG	Pettingill, Phil	California ISO
TAG	Rodriguez, Alonso	Southern California Edison
TAG	Torre, Bill	San Diego Gas & Electric
TAG	Wegner, Bud	San Diego Gas & Electric
TAG	Clairmont, Bernie	EPRI
Research Team	Abbey, Mike	EDM International, Inc.
Research Team	Clairmont, Bernard	EPRI
Research Team	Hurst, Neil	EDM International Inc.
Research Team	Light, Glenn	Southwest Research Institute
Research Team	Pandey, Arun	EDM International, Inc.
Research Team	Peyrot, Eric	Power Line Systems, Inc.
Research Team (Project Manager)	Stewart, Andy	EDM International, Inc.
Research Team	Tennis, Richard	Southwest Research Institute

2.2. Prototype Sensor Systems

A schematic of the prototype sensor system is shown in Figure 2-2. Besides the sensor for monitoring ground clearance/sag, the system consists of a data logging unit, communication equipment and power supply equipment. The entire sensor system can be grouped into three major components as follows:

1. Sensor – Pulsed Laser (LDM) or Machine Vision (PSTM) based sensor for measuring conductor ground clearance/sag including the target and any illumination needed for night-time operation,
2. Electronics Box – Data logging, communication and other associated hardware, and
3. Power Box – Surge protection, charger and battery backup for AC powered system, and solar panels, batteries and control for solar powered system.

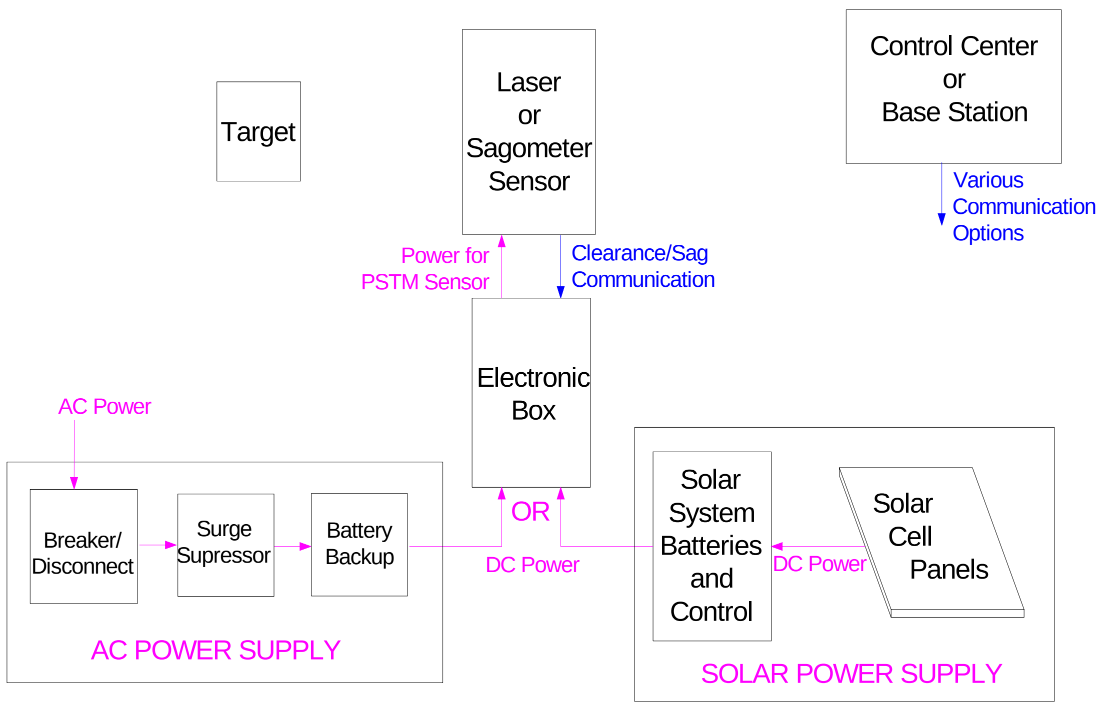


Figure 2-2 Schematic Showing Major Components of the Sensor System

2.2.1. Functional Specifications for the Sensor Systems

Functional specifications for the sensor systems were developed to guide the sensor hardware and software design and development. Detailed functional specifications are provided in Appendix A. Functional specifications for the hardware consisted of the operating specification, descriptions of environmental conditions under which the hardware must operate; accuracy, reliability and durability requirements; installation requirements; and power supply, data storage and communication requirements. In addition, the specifications addressed the needs for integrating measurements of ancillary variables such as wind speed and conductor temperature which are useful data when conducting rating studies.

2.2.2. LDM Sensor

Operating conditions, measurement accuracy, package design, power requirements, and communications were considered in the design for the laser distance measurement (LDM) system for monitoring line sag. The following sections describe work conducted in these areas for the LDM system. The final section provides a conceptual design for the entire package used to fabricate the pre-prototype system used in the acceptance testing of the sensor.

2.2.2.1. Background on Laser Distance Measurement

There are two well-developed techniques of distance measurement using a laser. These techniques are a time-of-flight (TOF) measurement of a laser pulse and the measurement of the phase shift of a modulated continuous-wave laser beam.

The time-of-flight approach to measure distance uses a laser beam pulse directed at a target and measures the duration of time between the emission of the pulse and its return from the target. The distance is calculated from the time of flight measurement using the velocity of the laser beam pulse (speed of light) in the medium. This procedure is repeated several times in quick succession to obtain a mean value.

Distance measurement using the phase shift technique, also called beam-modulation telemetry (BMT), uses a continuous-wave laser beam emitted from the rangefinder that is directed at the target. The laser beam's amplitude is modulated at a certain frequency that is selected based on desired range of measurement. The phase of the beam reflected back to the laser is compared to the phase of the beam emitted by the laser and the difference in phase is used to calculate the distance.

In theory, the two methods each have advantages and drawbacks. The time-of-flight system is fundamentally less accurate than beam-modulation telemetry. Causes of inaccuracies in the time-of-flight technique include: (1) changes in the shape of the beam pulse produced, (2) variations in the illuminated point on the target, and (3) the accuracy of the time-of-flight measurement. However, time-of-flight systems are widely used when their accuracy is acceptable. Causes of inaccuracies in the beam-modulated telemetry technique include: (1) turbulence in the air between laser and target, (2) changes in the air's index of refraction in the laser's path, and (3) instability of the circuitry to produce the modulation and measure the phase shift.

2.2.2.2. Selection of Laser Distance Measurement Device

Testing was performed to aid in the selection of the type of sensor, i.e. TOF or BMT-based sensor, to utilize in the LDM system. Two devices were selected for evaluation for the purpose of determining the accuracy of distance measurements made using the two theories of operation. The functional specifications of the selected TOF sensor and BMT sensor were compared to the functional specifications developed for the LDM system.

The key differences in the two systems compared to the LDM functional specification requirements pertain to the operating and storage temperatures. The TOF system meets the operating temperature specification, but has a storage temperature range that is approximately lower than that included in the functional specifications. The BMT system meets the upper limit of the operating and storage temperature ranges, but does not satisfy the lower limit of the operating temperature range.

2.2.2.3. Laboratory Evaluation

Since the primary purpose of using either the TOF or BMT technique for the LDM is to accurately measure distance, experiments were conducted in a laboratory setting to determine their measurement accuracies. The experiments enabled evaluation of the effects of target surface (smooth versus rough concrete), lighting conditions (bright sunlight versus darkness), rain, and distance on measurement accuracy. Both sensors were fixed to a tripod base for stability during the distance measurement tests. Four distances were marked from the target location to the rangefinder position: 25, 50, 75, and 100 feet. At each distance, 25 measurements were taken with each sensor to obtain an estimation of their accuracy and repeatability.

Two different targets were used which had different surface finishes. One had a very smooth concrete surface, and the other had a rough concrete surface. A 1-inch diameter circle was drawn on the surfaces of each target for aiming of the sensors. First, distance measurements were taken from each target in bright sunlight. Then, distance measurements were taken from only the smooth target in the presence of water sprayed along the axis of the laser beam. The purpose of this experiment was to assess the impact of rain on measurement accuracy. Finally, measurements on the smooth surface were conducted at night. Again, each sensor was tested at each of the four distances.

Based on the test results, the TOF sensor was not acceptable for use in the LDM line sag-monitoring tool since the system was not capable of making accurate measurements in sunlight, rain, and darkness. The results of the testing showed that the BMT sensor meets or exceeds the required measurement accuracy.

2.2.2.4. LDM Sensor Conceptual Design

The LDM sensor consists of the LDM module for measuring sag/ground clearance, the communications module to communicate to the electronics box, and the power supply module. Two options were considered for housing and mounting the LDM sensor.

The first approach was to place the complete LDM sensor inside a marker ball, as shown in Figure 2-3, that can be placed on an energized conductor. Several manufactures make marker balls that are designed to be mounted on conductors to warn pilots of the presence of power lines. The balls range in diameter from 9 to 36 inches. They separate into two hemispheres and are easily attached on the line while the line is energized. Some of the balls have a conductive coating on the inside to protect instruments inside the ball. The balls can be attached to conductors so that when the conductor rotates due to heating or wind, the vertical orientation of the ball remains unchanged.

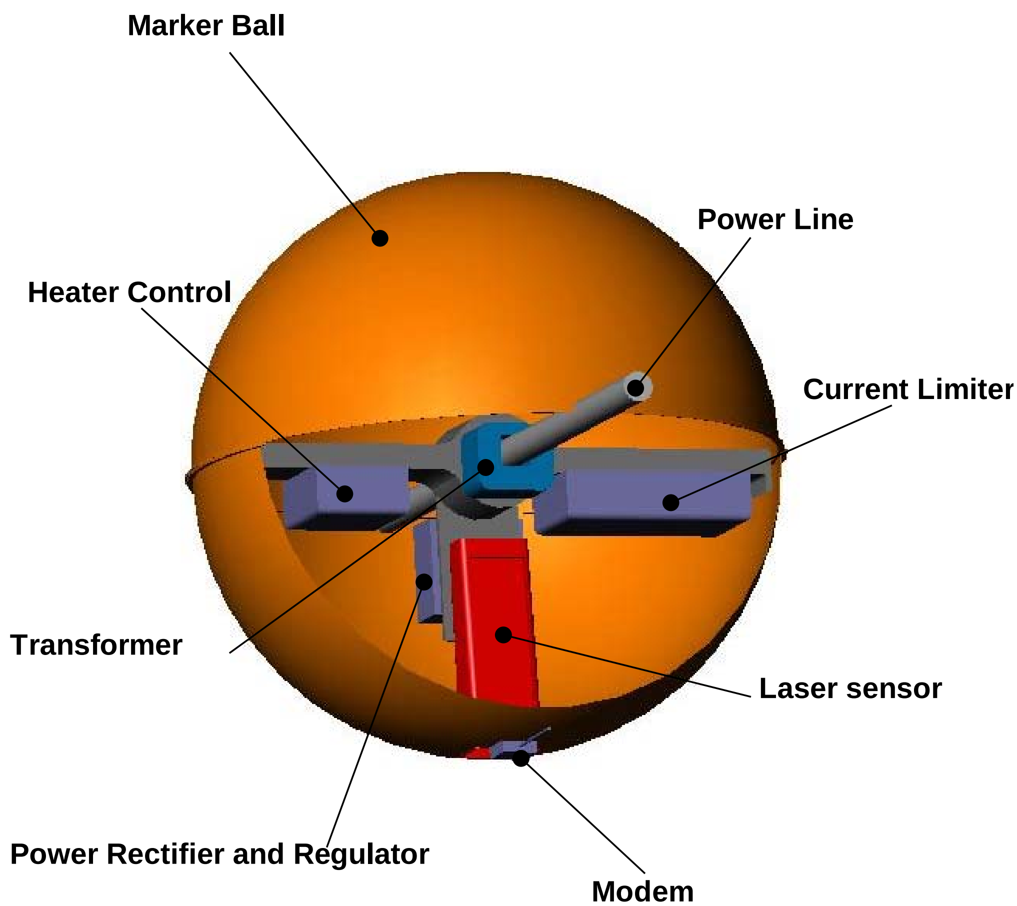


Figure 2-3 Conceptual Design of the LDM system Mounted Inside a Marker Ball

The second approach was to house the LDM sensor in a custom weatherproof enclosure that could be attached to a clamp designed to be mounted on conductors using a hot stick (Figure 2-4.) Because of the ease of installation and the simple design, it was decided to base the prototype system on this approach. The clamp selected for mounting the LDM enclosure was from SensorLink, a manufacturer of high voltage sensors. In fact, the inductive power supply for the LDM sensor was adapted from one of the sensors from SensorLink.

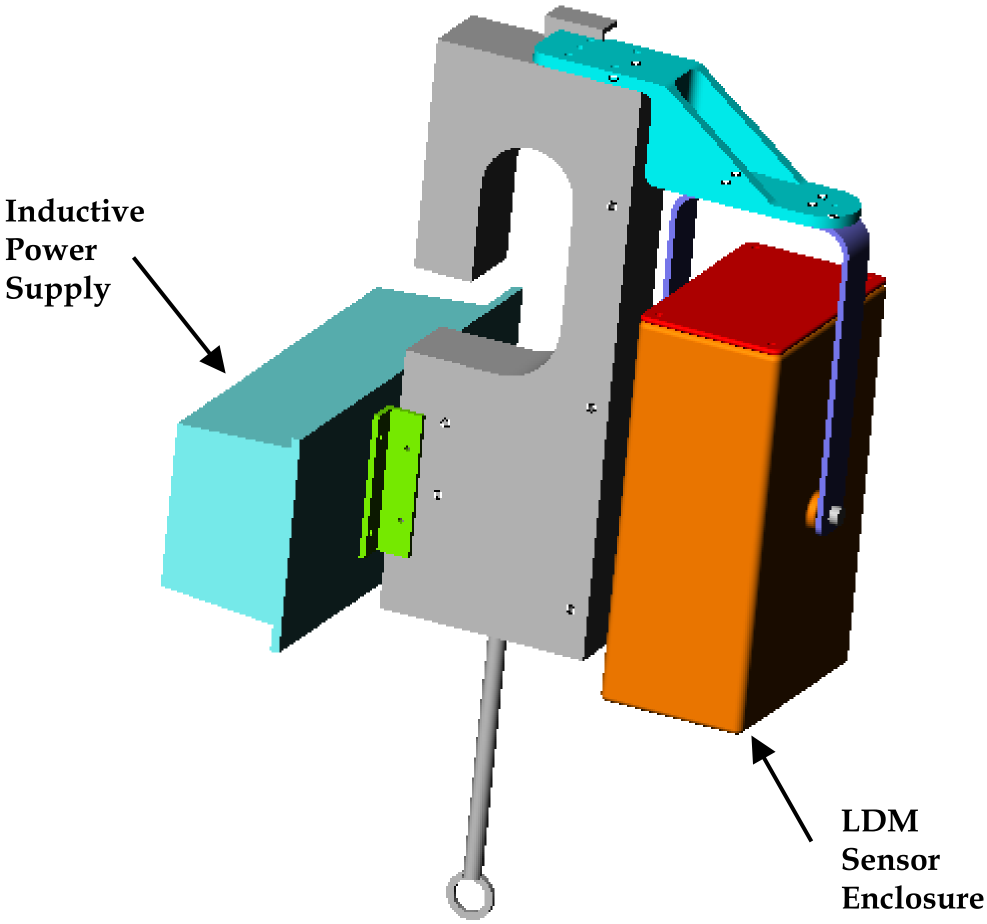


Figure 2-4 Conceptual Design of LDM Sensor Housed Inside a Custom Enclosure Mounted to a Clamp

2.2.3. Sagometer (PSTM Sensor)

The Sagometer measures the ground clearance by monitoring the position of a transmission line conductor with respect to the ground using an image processing technology. A typical installation for a Sagometer sensor is shown in Figure 2-5. The Sagometer consists of an image capture/processing unit mounted on the pole or tower on one end of the span and monitors the position of the conductor or a target attached to the conductor a fixed distance away.

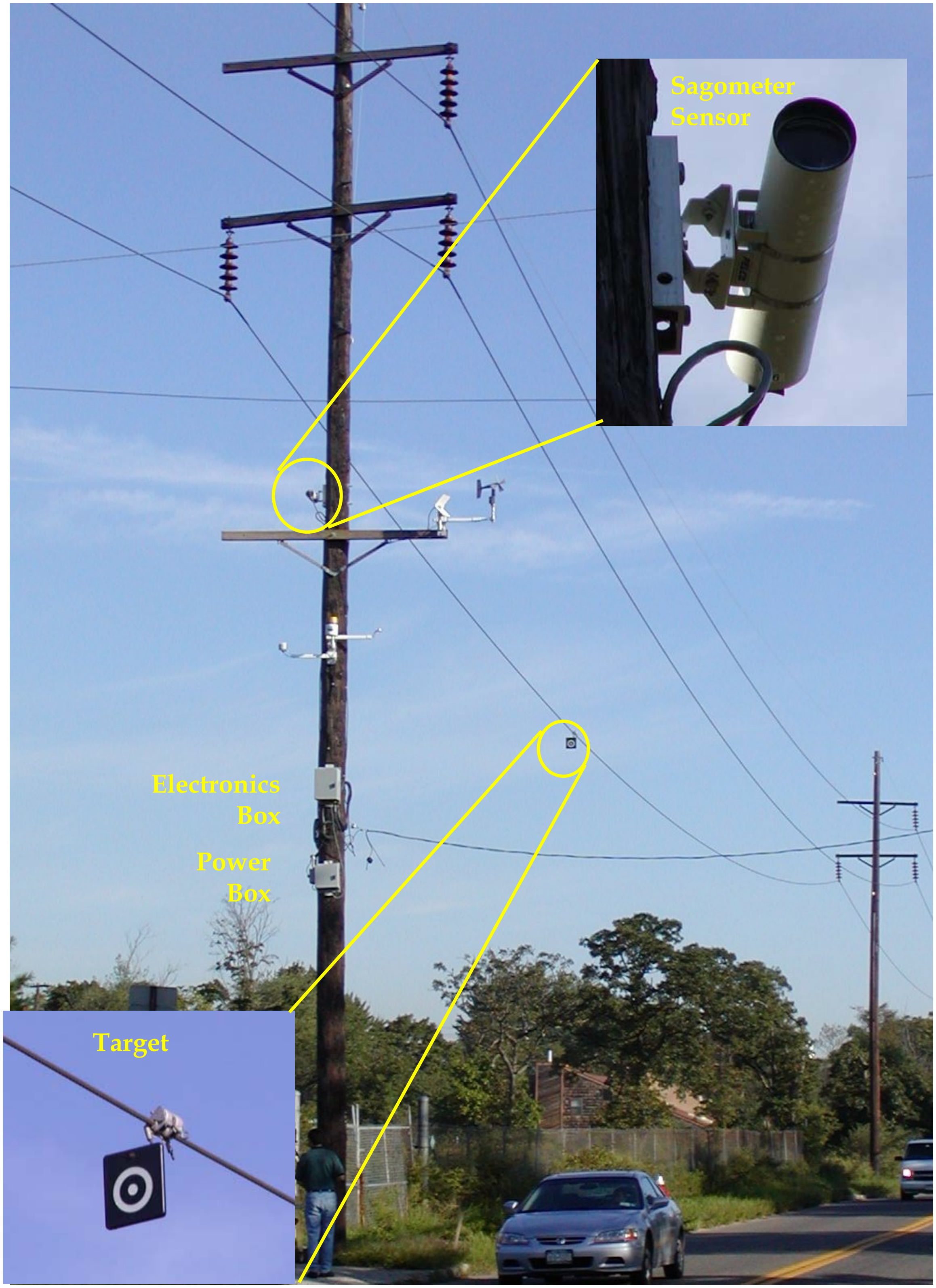


Figure 2-5 Typical Installation of PSTM System

The feasibility of the video approach to measuring conductor clearance/sag was proven in an earlier EPRI sponsored project. A functional prototype system was developed and installed at the EPRI Lenox facility in 1998 for extensive field evaluation under realistic field conditions. This functional prototype used a desktop computer to perform the image capture and processing to determine the ground clearance.

The successful performance of the functional prototype under realistic field conditions led to another EPRI sponsored project to develop a complete self-contained prototype system. A prototype video sagometer complete with rugged single board computers to perform the processing and solar power supply was developed, delivered and installed at the Lenox facility in January 1999. The system has been functioning successfully at the Lenox facility since the time of installation. The Sagometer was installed at a few utility sites across the country. These Sagometers have now been in the field for over a year and have performed exceptionally well with only a few minor glitches. Several improvements and enhancements have been incorporated in the Sagometer since the first prototype was installed at Lenox.

Although the first generation Sagometer proved to be successful in the field, significant opportunities existed to improve, simplify and miniaturize the system. First generation systems were deployed at several utilities including Public Service of New Mexico (PNM), Tennessee Valley Authority (TVA) and Southern Company.

The focus of this project has been on development of a second-generation Sagometer that will leverage upon some of the emerging technologies in the image process industry. The second-generation system uses a smart vision based system to integrate the image capture and processing tasks into a single miniature system. Work on the second-generation system was jointly funded by Energy Commission, EPRI and EDM.

Details of the key components and the functioning of the Sagometer system are presented here.

2.2.3.1. Principle of Operation

The system uses an imaging system to monitor the location of the conductor or a target attached to it. The imaging system is installed on either a transmission line structure or any other structure with a view of the span being monitored. The field of view of the imaging system remains the same at all time and the location of the conductor or the target in the view changes as the conductor moves up, down, or horizontally. Image processing technique is used to determine the location of the conductor or the target attached to the conductor in the cameras field of view. The search algorithm uses a pre-selected sub-image of the target (see Figure 2-6) and searches the image to determine the most likely location of the target in the camera image. The key for the success of this approach is to have a target with unique features that cannot be easily found in the background.

The change in vertical position of the conductor in the image is directly related to the change in ground clearance/sag. At the time of installation, location of the conductor or the target attached to the conductor in the imaging system's field of view is calibrated to the measured ground clearance/sag. Ground clearance/sag at any later time is obtained from the measured change in location of the conductor using calibration constants obtained at the time of system calibration. The resulting clearance information may be made available on a real-time basis using telemetry and/or logged in a datalogger for historical study.

Figure 2-6 A Typical Image of the Camera View and the Kernel Used for Correlation

2.2.3.2. System Components

The main component of the Sagometer is an image capture/processing unit. This unit captures an image, upon request or at a set interval, of the span being monitored, performs image processing to locate the conductor or the target in the image and calculates the ground clearance/sag. In the second generation Sagometer system all these tasks are performed by smart machine vision system. The processed data is stored in a datalogger for real-time downloads or historical downloading using telemetry.

Machine Vision System

The image capture/processing unit is the central component of the Sagometer system. This unit captures an image of the span being monitored, digitizes the image, processes the image to locate the target, calculates the ground clearance and communicates the data to the data-logging unit.

In the first-generation video sagometer, these tasks were performed using a combination of a CCD camera and a computer equipped with a frame grabber card. The second-generation systems use a smart vision based sensor that can perform all the image capture and processing tasks.

The smart vision systems are compact and combine all the image capture and processing capabilities into a single unit. These systems use a monochrome CCD imager with direct to memory image acquisition and a built-in Power PC processor or digital signal processor (DSP) that can be programmed to perform image-processing tasks. The image is directly read into the memory in digital form for the processor to perform the image processing tasks. The processor calculates the ground clearance from the captured image and transmits the data to a datalogger.

Target

The target is designed to provide a unique pattern for the imaging system. The target dimensions and the pattern used are shown in Figure 2-7. Retro-reflective tape is used to form the circular rings of the target. A symmetric pattern was used to avoid the shape being distorted if the target gets rotated due to wind. This helps avoid some of the complexities in the image processing algorithms. The target is mounted to a hotline clamp, allowing it to be installed on the conductor while energized using a hot stick.

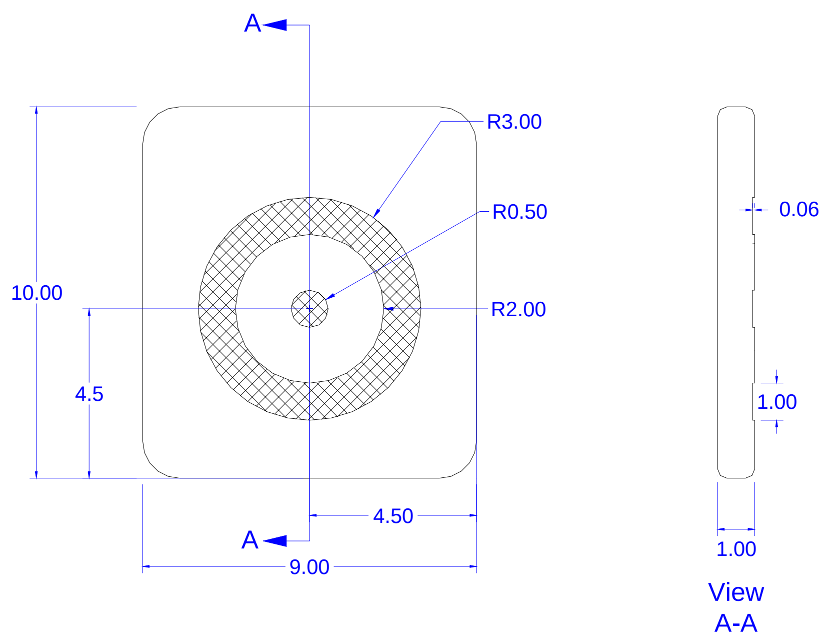


Figure 2-7 Target Dimensions

For nighttime operation and during periods of poor daylight visibility, the target is illuminated using diode lasers or LED illuminators mounted near the imaging unit. Two low powered laser diodes with their lens adjusted to illuminate the entire field of view of the imaging system are used to illuminate the target. The illuminated target is not visible at night from ground because of the retro-reflective material used in the target design.

2.2.3.3. System Operations

The firmware for the first-generation system was modified to function on the new second-generation systems. The firmware development environment of the DSP used in the machine vision system is somewhat different from the first-generation system's standard PC architecture. The firmware required some fundamental changes to compensate for these differences. For instance, the memory available with the machine vision system is much smaller and divided between program space and data space. This division requires the use of program overlays, which added complexity and a higher degree of compartmentalization of the firmware. Another difference is the lack of hardware floating-point implementation in the DSPs. In order to get reasonable performance due to the low speed of floating point emulation, the routine used for image processing had to be converted from floating point operations to primarily integer operations.

System Calibration

The calibration process is used to select a kernel that will be used in the image processing to locate the target in the image and to determine the two conversion factors needed to determine the ground clearance/sag from the location of the conductor or the target attached to the conductor. The first factor converts the location of the conductor in the image from pixels to feet and is called "pixels per foot" (PPF). The second factor is an offset that is needed to convert the measurement from a location in the field of view of the system to a clearance above ground.

The system is pre-calibrated in the lab prior to shipping to the field. The pre-calibration process consists of selecting a kernel and determining the pixels per foot (PPF). The only calibration needed in the field is to determine the offset which is obtained after installation from a survey measurement of the actual clearance at the target.

Normal System Operation

During normal system operation, the system performs the following tasks at periodic intervals.

- Grab an image
- Find the position of the conductor or the target within the frame
- Calculate the ground clearance and horizontal location
- Communicate the results to the datalogger
- Go into low power sleep mode for a predetermined interval.

The system continues performing these tasks until interrupted by a reboot signal from the data logger, a power glitch, or entry of commands from an externally connected keyboard.

<u>Image Acquisition</u> – An image is digitized by dynamically accessing the CCD memory of the machine vision system. The video data are then transferred to a buffer where, for each pixel in the image, a corresponding byte of data contains one of 256 gray levels. A value of 255 is a white pixel, while a value of zero is black.

<u>Target Location</u> – The target is located in the image data in the buffer using image processing algorithm. The image processing routine returns the horizontal and vertical pixel values of the center of the target in the image and a coefficient (0 to 1) which is a measure of how well the target location matched the stored kernel.

Clearance Calculation – The ground clearance and the horizontal location are calculated from the pixel location using the calibration constants. The horizontal location is from the location of the conductor at the time of calibration.

Data Storage – The ground clearance, the horizontal location of the conductor, and the correlation coefficient are then transmitted in ASCII form to the datalogger. The datalogger time-tags this data upon receiving it and stores it. The data from the datalogger is available for real-time or historical downloads.

System Timing and Power Conservation – The system timing can either be controlled by the imaging system or by the datalogger. In the those cases where the system timing is controlled by the imaging system directly, the real time clock of the machine vision system is used to time the interval at which measurements are taken. The datalogger can also be used to externally trigger the imaging system at a predetermined interval stored in the memory. In between measurements, the system goes into a sleep mode conserving power.

2.2.4. Electronics Box

The electronics box houses the data logging unit, communication equipment for communicating to the sensors and the control center, and other electronics needed for obtaining voltages needed and controlling different sensor components. A variety of communications options are available for communication between the electronics box and the sensor and the control center. The communication equipment housed inside the electronics box depends on the selected mode of communication and could range from cell phones, modems and wireless radios.

Datalogger

A datalogger is used for storing the measured ground clearance, sag, and/or horizontal position of the conductor. The datalogger receives the measurements from the vision system using serial cables. The datalogger is a stand-alone unit capable of recording and processing a variety of analog and digital inputs. These inputs allow for the connection of various ancillary sensors such as temperature probes, anemometers, and rain gauges. The datalogger has a circular memory that allows for continuous data storage and once the memory is full, the oldest data is overwritten first.

2.2.5. Power Supply for the Sensor Systems

The PSTM and LDM systems both include data logging units that will most often be mounted on a transmission line structure and can be powered using AC or solar power. In addition, the LDM sensor mounted on the conductor will need to incorporate an inductive power supply to avoid having to change batteries on a regular interval.

Figure 2-8 illustrates the basic types of power sources utilized for the Sagometer and the LDM systems. For illustrative purposes, the remote station/data logging component of the LDM system and the Sagometer system are shown with AC power and solar power sources, respectively. Both power supply options are viable for the system components.

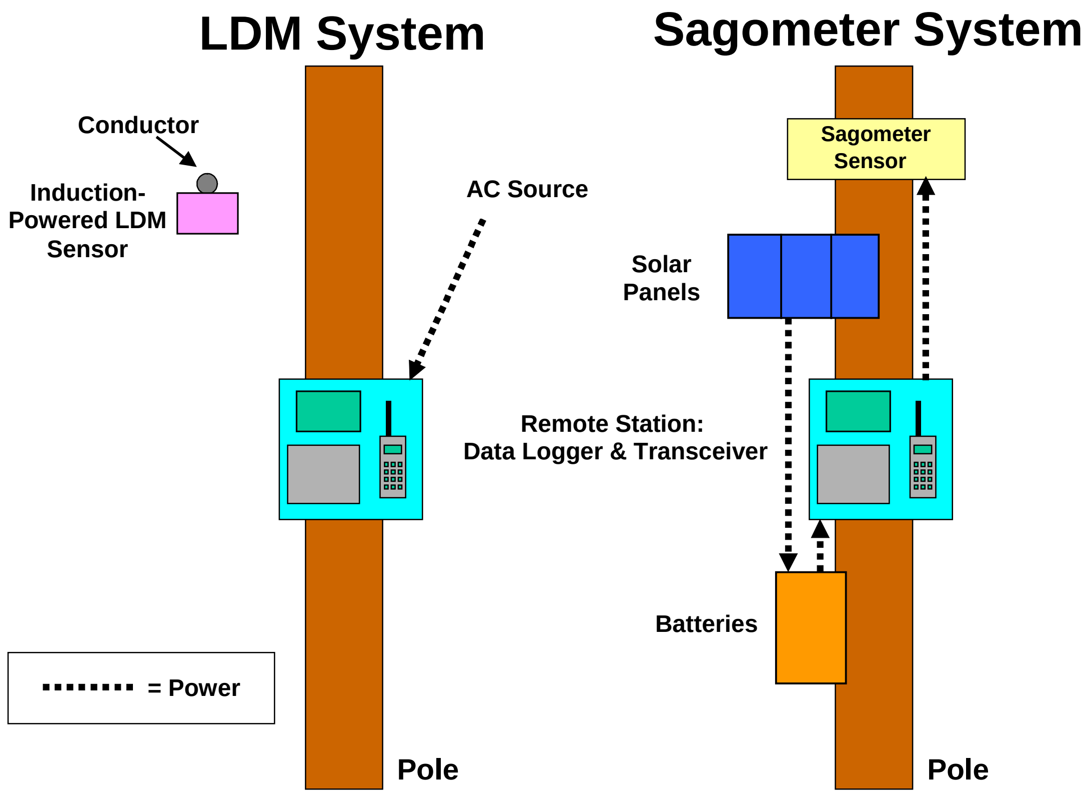


Figure 2-8 LDM and PSTM System Power Supply Components

2.2.5.1. Power Supply for the LDM Data Logging Unit and PSTM System

The power consumption for the LDM data-logging unit and the Sagometer system varies depending on the selected communication option and the data transmission rate.

Table 2-2 provides an estimate of the power requirements for the different major components in the LDM data-logging unit and the Sagometer system. Two options are available for providing power to the LDM and Sagometer systems. The power supply to be utilized for a specific installation depends on the constraints of the location, e.g. availability of a nearby distribution.

Where available, AC power is the most cost-effective option providing the greatest flexibility in terms of choice of communication and data collection/transmission rates. Solar power is a cost-effective option for locations where AC power is not practical.

AC Power

The AC power source is connected to a breaker/disconnect box and then to a surge arrester prior to being fed into the system. An uninterruptible power supply (UPS) is placed in line to avoid system failure during momentary power outages.

Table 2-2 Current Requirements for the Components Used in the Sensors

Component	System		Current (mA) @ 12 V Operating Mode	
	Sagometer	LDM	Stand-By	On-Line
Sensor System				
Illuminator	X			83
Data Logger	X	X	13.0	46
Machine Vision System	X			417
Communication Options				
RF Transceiver	X	X	65.0	650
Cell Phone/Modem	X	X	0.6	1940

An AC to DC converter is used to obtain the DC power needed for the sensor and the datalogger. The converter provides 12 V DC output from which other voltages needed are obtained using DC-to-DC converters.

Photovoltaic Power

A prepackaged photovoltaic power supply is used for installations where AC power is not available. The system consists of a solar cell array and an enclosure containing batteries and necessary circuitry. The solar system generates 12 V DC from which other voltages needed are obtained using DC-to-DC converters. The specific requirements of the solar power system (e.g., the number and size of photovoltaic panels comprising the solar cell array and the number of batteries) is selected based on the solar insolation available at the installation site and the power requirements for the system.

2.2.5.2. LDM Sensor Power Supply

The sensor component of the LDM system (i.e., the component to be attached to the conductor) requires approximately 4 W of power to operate. This power is obtained directly from the power line by magnetic induction. Magnetic induction requires that a pick-up coil or transformer be located close to or around the power line conductor such that the plane of the coil is orthogonal to the magnetic field existing around the conductor when an AC current is flowing. The power induced through the transformer is proportional to the current, the number of turns, and the coupling efficiency. Commercially available current transformers (CT's) are commonly used for this purpose on lower voltage lines; they consist of a laminated metal core around which a wire is wound to form a coil. The core completely encircles the conductor for optimum induction. Split core transformers are manufactured with the core fabricated in two C-shaped sections that are latched together to form the complete encircling core for applications such as the subject application where it is not feasible to disconnect the conductor and feed it encircle the line. Use of induction coil results in a significant loss in efficiency and requires power to be stored in a rechargeable bank of batteries. The batteries are charged between laser measurement cycles and would then provide the higher current demand needed during the measurement cycle.

Other circuits needed for conversion of the induced AC power to the DC voltage levels required by the LDM sensor are described below. A conceptual block diagram of the power supply for the LDM sensor is provided in Figure 2-9.

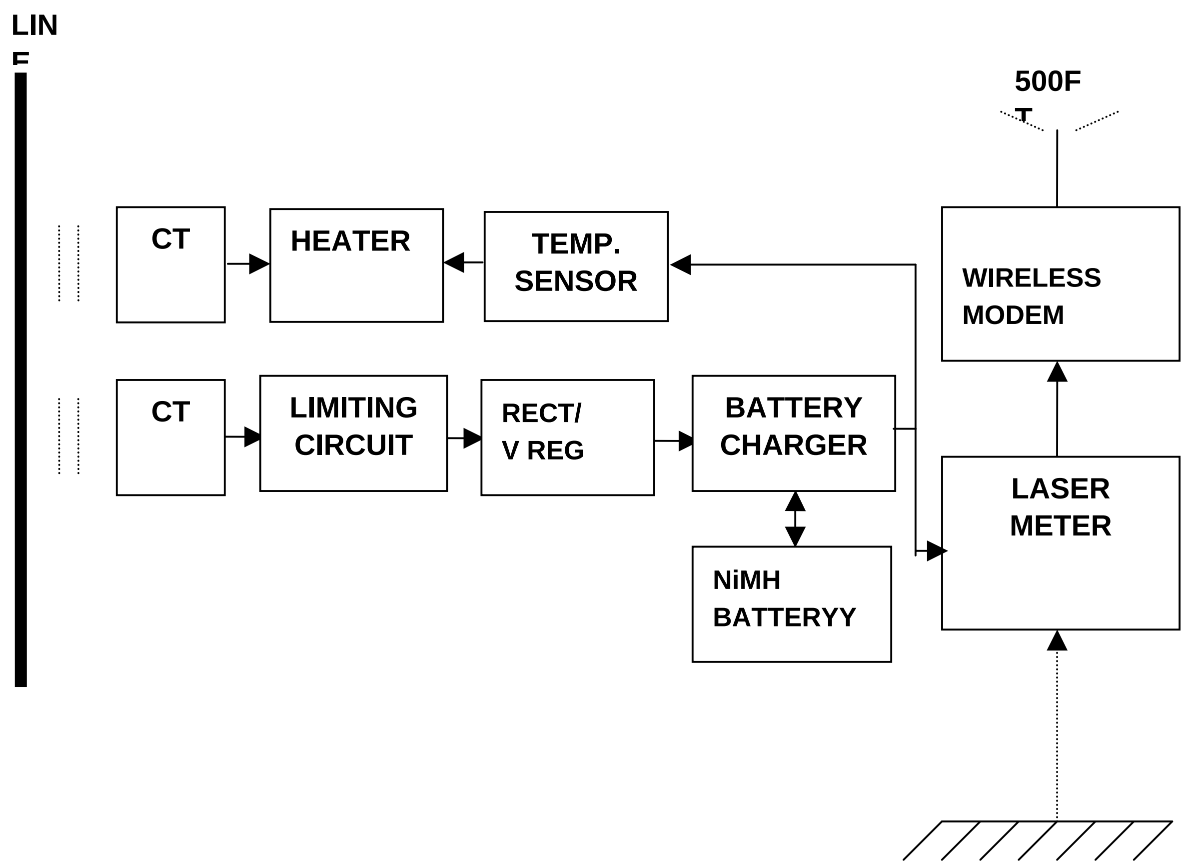


Figure 2-9 Power Supply for LDM Sensor

Power Limiter Circuit

Since the power line current may vary over a very wide dynamic range ratio of 40:1 (100A to 4000A), a power limiter circuit was needed between the CT and downstream electronic devices to protect against malfunction or damage due to voltage overload or excessive heating at high current levels. The power limiter circuit senses the induced voltage level in the CT secondary and changes CT winding taps or switches-in additional series resistance to limit load current in response to significant increases in the induced power. Voltage clamping is also employed to ensure that the input voltage to the rectifier and voltage regulator circuits remains within the safe operating range.

Rectifier and Voltage Regulator Circuit

A full-wave rectifier and voltage regulator circuit converts the AC induced voltage to DC for powering the laser and wireless modem, as well as the battery charger circuit in the event that batteries are determined to be necessary for storing power.

Battery Charger Circuit and Battery (fall-back approach)

For reliable operation of the laser measurement system a battery charger circuit and battery can be added for power storage between laser measurements. This reduces the power requirements of the CT, since less power is used during the quiescent period between measurements, i.e., when the laser is not active and communication activity is reduced. During the quiescent period a charge can be accumulated in the battery for use during the subsequent measurement and data communication.

A NiMH type battery was used for this application, since it has high storage capacity, does not exhibit a memory effect, is safe to use and environment friendly (does not contain lead, mercury, or cadmium), performs well at low temperatures, and has good recharge cycle endurance.

Heater Circuit (optional)

For LDM sensor installations in cold climates, it might be necessary to extend the laser measurement capability over a wider ambient operating temperature range. For these cases, a heater circuit including a separate CT, heating element and temperature control sensors is added to the sensor package. In instances where very cold weather occurs coincident with low levels of power line current it is expected that insufficient power might be available for heater operation and laser distance measurement may not be possible. However, this is not considered a serious problem, since during cold weather and low-current conditions conductor sag is generally not a concern. At higher current levels, when excess power is available from the CT and line sag is of much greater concern, heater operation could be enabled to extend the operating range of the laser. Temperature sensors would provide thermostatic control over the heater.

2.2.6. Communication for the Sensor Systems

A communication system is needed for both the Sagometer and the LDM systems to communicate data from the site being monitored to a desired location such as an engineering office or an operations/control center. In addition, for the LDM system, a communication system is needed to transmit the measured clearance data from the LDM sensor mounted on the conductor to a data-logging unit/base station located nearby. Figure 2-10 illustrates the basic components of the communication systems for both the PSTM and LDM systems.

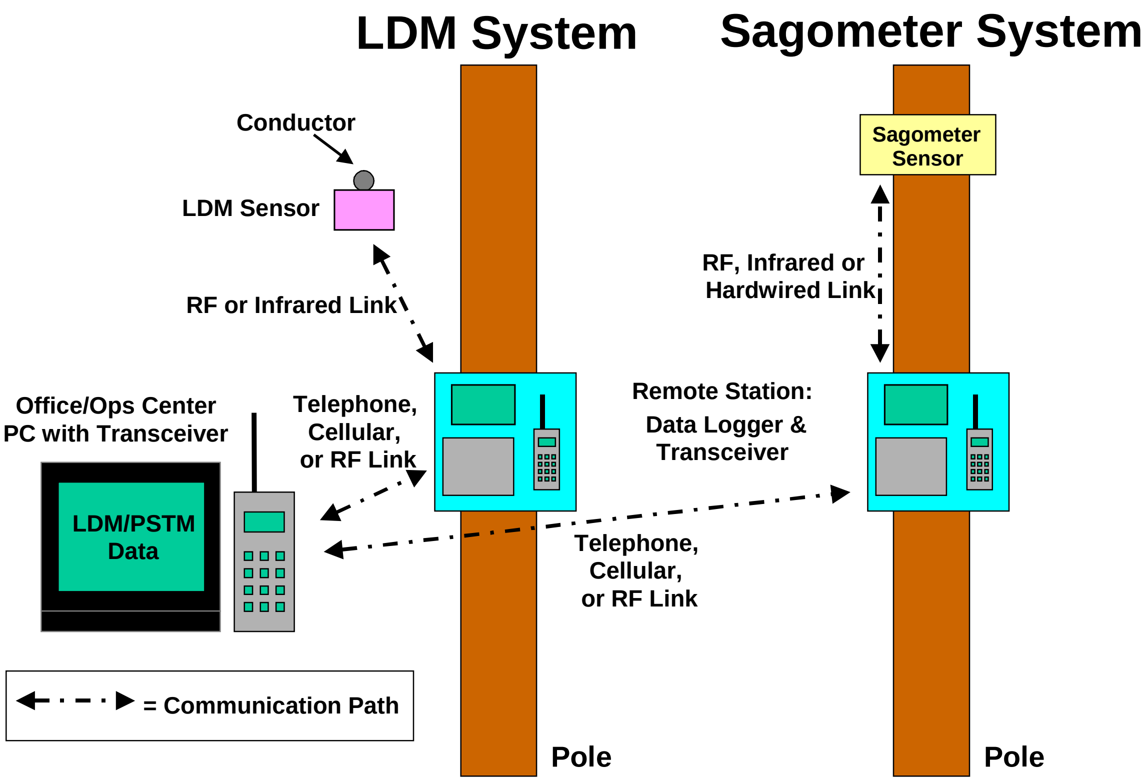


Figure 2-10 LDM and PSTM Communication System Components

2.2.6.1. Communication between LDM and Sagometer Base Station and Remote Site

The LDM and Sagometer data logging unit/remote station needs to be able to communicate with a base station terminal, e.g., a PC in an engineering office or a control/operations center PC or workstation that may be located at a distance of up to several hundred miles away from where sag measurements are made. For most line rating studies historical data will be downloaded on a regular interval. For real-time rating applications data communication needs to be on a real-time basis. The systems also need to be capable of interfacing with SCADA systems.

Both the LDM and Sagometer remote stations incorporate a datalogger to record clearance measurements. The same datalogger specification/design works for both the LDM and Sagometer systems. The datalogger selected for the system can be interfaced with a variety of communication options including radio, telephone, cellular and satellite links to transfer the necessary information to a remote site. Some of these options are more suitable for historical data downloading than real-time applications. The datalogger also has a mode that allows it to be connected to SCADA systems that support MODBUS RTU protocol. The most common connections from base stations to SCADA systems will be direct, hardwired links and radio links.

Telephone and Cellular Communications

A telephone line (hardwired) or cellular communication link can be used to communicate between the base station and the remote site. In general a direct connection to a telephone line provides a cost-effective and highly reliable medium for communication. Unfortunately, direct connection to a telephone line is only practical in locations where systems are installed adjacent to existing telephone lines.

Analog cellular service is generally reliable and provides fairly good geographic coverage. Directional antennas can be used to improve the signal strength for the cellular link. Unfortunately, even when directional antennas are used service may not be available/reliable in some remote areas.

While direct connection to telephone lines is somewhat more reliable for real-time operation, cellular service can be used if the cost of cellular service is not considered prohibitive.

Spread Spectrum Radios

Spread spectrum radios can be used for communication between the base station and a remote site. The design of the radios to be utilized provides reliable communications for distances of approximately 15 to 20 miles. Repeaters can be used to extent the range further. A direct line of sight is needed for the radio link to work. The radios can be combined with repeaters or they can be connected to a phone link to extend their range. Radios are appropriate for both real-time and historical data download applications. They can also be used as the medium for interfacing the base stations or the sensors directly with SCADA systems.

The specified radios operate near the 900 MHz frequencies and do not require FCC licensing. The radios are connected to a directional antenna to improve signal strength and communication reliability.

Low Orbit Satellite (LOS) Service

There are several different satellite services available today for reliably transmitting limited amounts of data. Some of these services have restrictions on the type, amount and/or rate of data transmission. Satellite communication options suitable for communicating between base stations and remote sites are described below.

The GOES and Argos satellite systems support one-way data transmission. The INMARSAT system supports two-way data communication.

Recently, ORBCOMM Communications launched several LOSs, which is dedicated to short burst communications. ORBCOMM has 24 LOSs so that continuous global coverage is provided. This approach allows a message of up to 1500 characters to be transmitted to the LOS and, then, to a utility site. ORBCOMM can also provide small, low-cost transceivers to interface with the data acquisition equipment using a RS232 port.

The satellite communication option is considered suitable for very remote sites where none of the other communication options are feasible. This option will be the most expensive to set up and has a recurring monthly cost that could be substantial.

2.2.6.2. LDM Communication to the Data Logging Unit

The communication system between the LDM and the data-logging unit located up to 1000 feet away needs to be a wireless point-to-point link. In operation, the data-logging unit uses the wireless link to periodically (perhaps once every 5 minutes) request the sensor to perform a measurement and transmit the data to the datalogger in the electronics box. The datalogger then logs the measurement for subsequent download to a base station.

In selecting a mode for wireless communications between the LDM system and the data-logging unit, three types of communication systems were considered: (1) radio (RF), (2) infrared (IR), and (3) laser communications. Radio communication was selected as the best candidate for initial use for this application. Summaries of the merits of each option are provided below.

Radio Communications

Radio signal transmission over short distances is less prone to degradation due to outdoor weather conditions such as rain, snow, or fog than IR and laser communications. Also, short distance radio transmission does not require precise alignment between the transmitter and receiver and is not prone to signal degradation due to dust, dirt, moisture, or other non-metallic contaminates. Vegetation growth should not affect radio transmission. Another advantage of radio communications is the availability of reliable, small, low-power radio modems that can easily interface with electronic measurement equipment for transmission of RS232 serial data over a wireless link.

IR Communications

Wireless IR modems communicate information by transmitting an IR light beam to a target IR receiver. The receiver must be within the field of view of the beam (typically 5 degrees) for reliable communications. IR signal transmission does not require an antenna. A penetration, or window, is required in the enclosures (i.e., the enclosures for the sensor and base station) to serve as the IR beam exit and entry ports. IR communication is not susceptible to RF interference if corona should occur in the vicinity of the LDM system.

The disadvantage of IR communications is that a clear line of sight is necessary between the transmitter and receiver. Movement of the power line resulting in the receiver being outside the field of view of the transmitter could disable communications. Inclement weather conditions, dust and dirt contamination, and objects in the beam path may result in unreliable or disabled communication. Also, low cost IR communication systems capable of transmission over distances up to 1000 feet are not readily available. Most IR systems are specified for communication distances of less than 100 feet. The project team was only able to identify one suitable commercial IR communication system claiming to achieve a 500-foot transmission distance. The modem required for this system is relatively large (7.5 x 5.5 x 5.5 inches) and heavy (2.1 lbs) and requires a considerable amount of power to operate (24 W). This system also requires a large penetration window in the sensor enclosure for beam transmission and reception. A large penetration reduces the effectiveness of the conductive Faraday shield required on the inside of the LDM sensor for corona prevention.

Laser Communications

Wireless laser communications require precise alignment of the laser transmitter and receiver for reliable data transmission. The potential for movement of the power line due to factors such as wind eliminates laser communications from practical consideration.

2.2.7. Acceptance Testing of Sensor System

Acceptance testing of the prototype sensors was performed at the EPRI high voltage facility in Lenox, MA. Tests were performed on a simulated span for which the ground clearance could be changed by feeding more conductor in to the span. Effect of high voltage and high current were simulated one at a time on the test span.

2.2.7.1. Acceptance Test for the Laser Distance Measurement (LDM) SYSTEM

The basic functions of the LDM system that must be demonstrated during an acceptance test are as follows:

- Production of Power by Induction from High Voltage, High Current Line – The ability to obtain power inductively from a live transmission line sufficient to charge the electrical circuits that power the laser device, the data acquisition system, and the wireless modem. The electrical load on the line for which this functionality must be demonstrated ranges from 100 to 2000 amps. This capability can be demonstrated separately from the rest of the functionality testing.
- Clearance Measurement – The ability to accurately measure conductor ground clearance/sag. These data should be collected in sunlight and darkness, and dry and wet conditions.
- Data Transmission – The ability to reliably transmit data from the sensor using a wireless modem over a distance of approximately 1000 feet while operating in the fields produced by varying amounts of current and line voltage.

Inductance Power Transformer Test

The induction power transformer unit consisting of the current transformer, current limiting circuit, rectifier, voltage regulator, and battery charging circuit was mounted on a test line. The test line was selected so that the current flowing through it can be controlled. The output of the induction power transformer was monitored for line currents covering a range from 100 to 2000 amps. To pass the test, the output of the induction power transformer unit measured at the input to the battery charger circuit must be at least 6 volts ±0.5 volts over the entire range of current. The battery voltage was also monitored to see if it is charging or discharging. A charging voltage will indicate that the output of the induction power transformer is sufficient to charge the batteries while taking measurements.

The goal of the test was to determine the ability of the inductive power transformer to supply charging voltage to the battery that will allow for the laser distance measurement (LDM) system to perform the data collection, data transmission and component heating functions under various line current conditions.

The measured voltage is the unregulated DC voltage that is developed by the charging circuit. The batteries were drained prior to testing to evaluate the charging circuit under the worst conditions. Voltage measurements were taken with both the heater circuit in the "on" and "off" mode. The battery voltage was also monitored to see if it was charging (increasing voltage) or discharging (decreasing voltage).

The data collected are shown in Table 2-3. From these data the following conclusions can be reached.

- Without the optional heater, even a line current of 100 amps will provide sufficient inductive power for the LDM system to function properly.
- With the optional heater, under the worst case scenario, where the laser, heater and the radio transmitter are operating simultaneously, a minimum of 500 amps is needed to provide sufficient inductive power to charge the batteries. However, the thermal control of the heater will turn the heater on and off at ambient temperatures of 30° F and 50° F, respectively. In addition, the housing containing the laser and modem is well insulated thermally to minimize the amount of time that the heater will be needed.

Table 2-3 Inductive Power Supply Test Data

Line Current (Amps)	Voltage Output (Volts)		Comments
	With Heater	Without Heater	
100	6.53	7.15	Discharging with Heater On
200	6.56	7.09	Discharging with Heater On
300	6.6	7.03	Discharging with Heater On
400	6.82	7.75	Discharging with Heater On
500	6.7	7.9	Charging
600	6.4	8.17	Charging
700	6.6	8.23	Charging
800	7.3	8.2	Charging
900	7.5	8.2	Charging
1000	7.19	8.18	Charging

Clearance Measurement Test

The clearance measurement test and the data transmission tests were performed at EPRI's high voltage laboratory in Lenox, MA. A test span where the clearance could be varied was used for these tests. The LDM sensor was mounted to the conductor and actual clearance measurements were taken using a tape measure as shown in Figure 2-11. A small section of the conductor with the LDM sensor was powered using a variac and a series of transformers as shown in Figure 2-12. Approximately 400 Amps of current was put on the conductor for the clearance measurement tests. The clearance was varied by feeding additional conductor into the span.

Figure 2-11 Clearance Measurement Test Setup

Figure 2-12 Variac and Series of Transformers to Generate High Currents on the Conductor

Table 2-4 provides the clearance measurement test data for the LDM sensor. Data were collected for five different clearance values ranging from approximately 10 feet to 30 feet. At least five measurements were taken at each clearance value. The maximum difference between the LDM sensor measurement and the tape measurement was 1.13 inches, which is within the ±2-inch accuracy goal for the system. During laboratory tests, the LDM system was found to be considerably more accurate; it is believed that the tape measurements may have more inherent error than the LDM sensor measurements due to variables introduced by the outdoor test environment.

The LDM sensor was left running overnight with 400 amps current on the conductor and data from the sensor was logged using a datalogger. The sensor worked throughout the night without any errors.

Table 2-4 LDM Sensor Clearance Measurement Test Data

Trial Number	Description of Environmental Conditions	Distance Measured Using Tape (feet)	Distance Measured by LDM (feet)	Average Difference Between Tape and LDM Measurement (inches)
1	Overcast, temperatures below freezing, with frozen snow on the ground.	30.17	30.13, 30.14, 30.13, 30.14, 30.15	0.38
2		27.47	27.39, 27.38, 27.38, 27.37, 27.37	0.91
3		18.92	18.83, 18.83, 18.83, 18.83,1 8.81	0.91
4		12.17	12.13, 12.13, 12.13, 12.13, 12.13	0.77
5		33.32	33.23, 33.24, 33.23, 33.23, 33.2	1.13

Data Transmission Test

The setup for the data transmission test was similar to that for the clearance measurement test. Instead of high currents, high voltages were applied to the line to see if they interfere with data transmission. The LDM sensor was operating using battery power as no current was flowing through the conductor. Data transmission was verified at distances of 200, 500 and 1000 ft. The line voltages at which tests were conducted were 138 kV, 230 kV and 345 kV. Tests were not conducted at 500 kV because of safety concerns. At least ten measurements were taken at each of the voltage and distance combinations.

Table 2-5 provides the results of the LDM sensor data transmission tests. The LDM sensor successfully transmitted data at all the voltage and distance combinations. Further, given the range of the radio modem, the LDM sensor should be able to communicate data over a much greater distance.

Table 2-5 LDM Sensor Data Transmission Test Results

Voltage	Data Transmitted Successfully at Distance (Yes or No)			Discussion
	200 ft	500 ft	1000 ft	
138 kV	Yes	Yes	Yes	
230 kV	Yes	Yes	Yes	
345 kV	Yes	Yes	Yes	

Summary & Conclusions

The laser sensor successfully passed all the acceptance tests. The inductive power supply can supply sufficient power for the sensor at a minimum of approximately 100 A without the optional heater. With the optional heater, the system requires approximately 500 A under the worst condition. The system can accurately measure clearance and successfully transmit data up to 1000 feet at various voltage levels.

2.2.7.2. Acceptance Test for the Sagometer system

The first generation prototype Sagometer system was developed and tested in 1998-1999 through a collaborative effort between EDM and EPRI. Since then several prototype systems have been installed for field-testing at utilities across the U.S.[2,3] The second-generation system developed as part of this project uses power supply and communication components/technologies that are very similar to those used in the first generation system. Since the power supply and the communication options have already proven to be reliable through the field trials of the first generation prototypes, the acceptance test will focus on the clearance measurement capabilities of the second-generation Sagometer sensor.

Power Supply

The capability to reliably power the Sagometer system has been demonstrated through the deployment of several prototypes of the first generation system at locations across the U.S.[2,3] Therefore, the capability of this component of the technology does not need to be demonstrated as part of the acceptance test. It is worthy of note that the second-generation sensor uses considerably less power compared to the first generation sensor system. This is a significant benefit that will enable reduction of the size/capacity of the photovoltaic system required for solar powered Sagometer systems.

Clearance Measurement Test

The second generation Sagometer system was installed at EPRI's Lenox, MA laboratory facility for acceptance testing. The camera and the illuminator were installed on a pole as shown in Figure 2-13. Figure 2-13 also shows a view of the span to be monitored. The target was installed on the conductor approximately 150 feet away from the camera. The system was calibrated to the ground clearance of the conductor at the target. For the clearance measurement test, the ground clearance was changed by feeding conductor into or out of the span. Clearance measurements were taken over a range of twenty feet. Because of the below freezing weather conditions, tests were only conducted at five clearance settings. However, a more thorough test of the clearance measurement was conducted at EDM's laboratory. Also, a system installed at EDM has been undergoing longer duration performance tests.

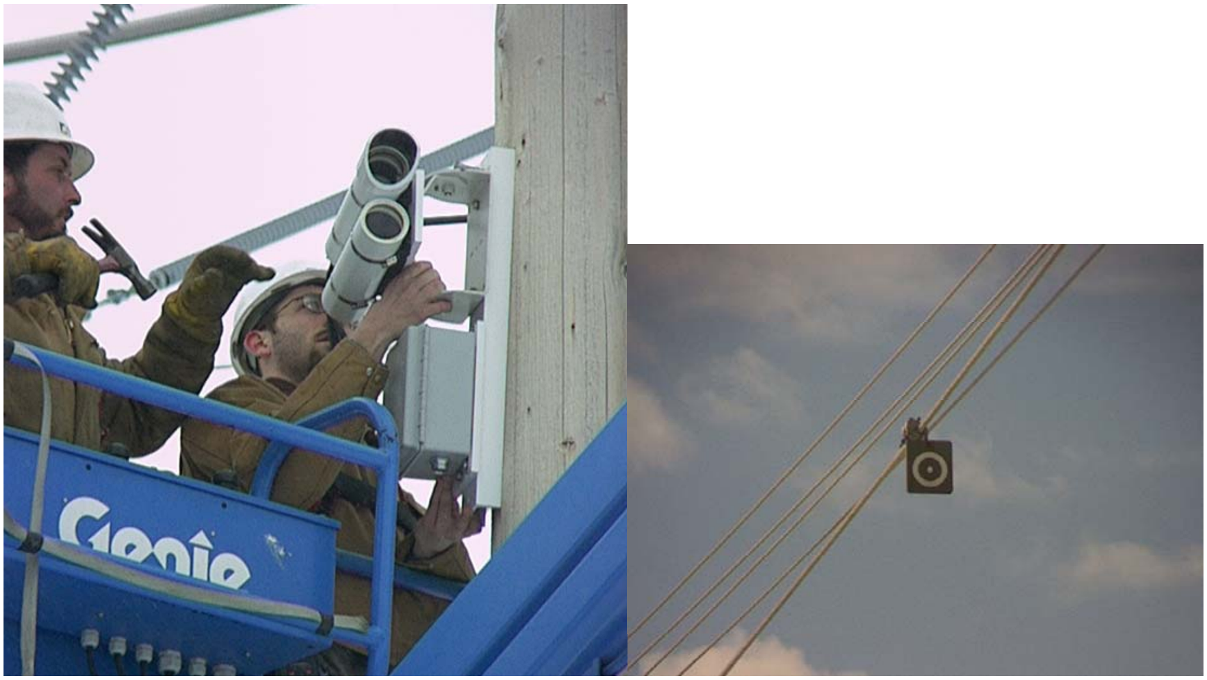


Figure 2-13 Sagometer System Installation at Lenox, MA for Acceptance Testing

Table 2-6 provides the clearance measurement test data collected at EPRI's facility. All the clearance measurements were within ±2 inches of the tape measurement with the maximum difference being 1.32 inches. During laboratory tests, the Sagometer system was found to be considerably more accurate; it is believed that the tape measurements may have more inherent error than the Sagometer sensor measurements due to variables introduced by the outdoor test environment.

Table 2-6 PSTM Clearance Measurement Test Data

Trial Number	Description of Environmental Conditions	Distance Measured Using Tape (feet)	Distance Measured by PSTM (feet)	Average Difference Between Tape and PSTM Measurement (inches)
1	Overcast, temperatures below freezing, with frozen snow on the ground	13.14	13.07, 13.09, 13.09, 13.07, 13.07	0.84
2		19.13	19.09, 19.09, 19.09, 19.09,1 9.09	0.48
3		26.56	26.63, 26.63, 26.65, 26.65, 26.65	1.08
4		32.28	32.33, 32.33, 32.36, 32.36, 32.36	0.96
5		36.86	36.95, 36.95, 36.97, 36.97, 36.97	1.32

Data Transmission

The ability to reliably transmit data from the system using radio and cellular phone communication options has been proven through the field testing of the prototype first generation systems that have been deployed at locations across the U.S. Therefore, testing of this component of the system will not be included as part of this acceptance test.

Summary & Conclusions

Based on the clearance measurement tests conducted at EPRI's facility and at EDM's laboratory, the Sagometer system passed the acceptance test. The system has also been successfully tested at night and during rain. Further, the system installed at EDM's facilities has shown the longer duration performance of the system to be acceptable.

2.3. Line Rating Software

The line rating software utilizes the PLS-CADD software from Power Line Systems, Inc. for designing new lines. The PLS-CADD software has a complex analysis engine used in the design process and also enables three-dimensional modeling of overhead lines and terrain. The use of the PLS-CADD software as the basis for the line rating module allowed the system to build upon theses unique and sophisticated modeling and display capabilities built into the software.

2.3.1. Line Rating Software Description

The line rating software obtains the data from the ground clearance/sag sensor and the loading data from the utilities systems and combines it with the PLS-CADD model to determine the steady state and emergency rating for the line being monitored. To make the line rating software function with any sensor providing a clearance measurement, it was decided that the software will read real-time data from a data file.

The process for obtaining a rating from clearance, weather and loading data for the line being monitored consists of the following steps:

- Calculate conductor catenary constants and effective temperatures from the measured clearance/sag:
  - For spans with clearance/sag sensors, catenary constants are obtained by fitting a curve through the clearance measurement at the target and the known span end points in the model. An effective wire temperature is calculated to match the catenary using sag-tension routines.
  - As it might not be always feasible to install the sensor in the most critical span or at the critical point on the span, the sensor measurements need to be extrapolated to the non-instrumented spans. Clearance/sag for the non-instrumented spans is calculated by assuming the same effective wire temperature as in the closest instrumented span. For adjacent spans within the same tension section this is usually a good approximation and is same as the ruling span approximation used in most sag-tension programs.

- Calculate clearances and critical temperature at all points along the span from the determined conductor position and model for ground terrain and obstacles. Determine critical temperatures at which clearances will be violated using sag-tension results.
- Calculating real-time ratings using IEEE standard 738. IEEE standard 738 requires following inputs to calculate conductor temperature:
    - Conductor temperature (effective) is available from sag-tension calculation,
    - Ambient temperature from is obtain from temperature sensor installed at the sensor or from a nearby weather station,
    - Solar radiation from instrument, weather station,
    - Current from an instrument installed at the span being monitored or utilities SCADA system,
    - Conductor properties is available from test or manufacturer and
    - Wind speed and direction is available from anemometers installed at the sensor or a nearby weather station. However, accurate point measurements of wind are of questionable value since wind can vary along span due to shielding effects of hills and trees. As conductor temperature is already calculated and all the inputs except for wind are know, an effective wind speed perpendicular to the line can be calculated using IEEE standard 738.
- Real-time ratings are then calculated as:
    - Real-time steady-state rating is the current that will cause the conductor to reach critical temperature in steady state. The critical temperature could be based on a clearance limit or can be based on a thermal limit depending on the line.
    - Real-time emergency rating is the current causing conductor to reach critical temperature in a certain amount of time.

The PLS-CADD line rating module consists of several graphical and textual screens that provide the real-time ratings for the line being monitored. A brief description of each of the screen is provided below.

2.3.1.1. Line Summary Dialog Box

Line summary dialog box, shown in Figure 2-14, displays a single row of data for each monitored circuit. Data in this box is updated real time as data is received from instruments.

Figure 2-14 Line Summary Dialog Box for the Line Rating Software

The columns in the line summary dialog box are described below:

Line Name – Name of line or circuit being monitored

Clearance margin – Minimum amount of excess clearance to the terrain or other obstacles in all of the selected spans in the circuit. Selected spans are either instrumented spans or other spans selected by the user because they are expected to control the maximum operating temperature.

Temperature margin – Temperature change which will make the clearance margin equal to zero.

Amps available – Current level at which program predicts the clearance margin will become zero.

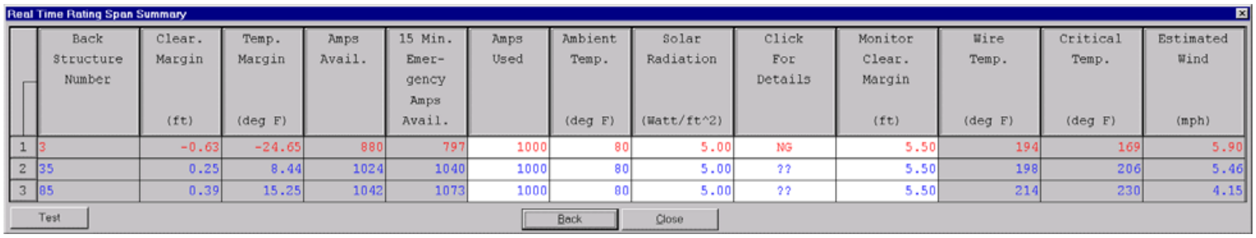
Emergency amps available – Emergency operation current which will make the clearance margin zero after a user designated time interval.

Amps used – Measured value of current flow

Click for details – Clicking this button takes you to the Span Summary dialog box described below where you can see details on the selected spans.

2.3.1.2. Span Summary Dialog Box:

The span summary dialog box, shown in Figure 2-15, displays details about all of the selected spans. Data in this box is updated real time as data is received from instruments. The white columns represent field measurements and the gray columns represent calculated values. Rows are color coded based on their clearance margins. Red indicates a clearance violation. Blue indicates a clearance margin between 0 and a user specified "critical clearance margin". Black indicates the clearance margin exceeds the "critical clearance margin". Clicking on the Back button returns to the Line Summary Dialog Box


Real Time Rating Span Summary

	Back Structure Number	Clear. Margin (ft)	Temp. Margin (deg F)	Amps Avail.	15 Min. Emer-gency Amps Avail.	Amps Used	Ambient Temp. (deg F)	Solar Radiation (Watt/ft^2)	Click For Details	Monitor Clear. Margin (ft)	Wire Temp. (deg F)	Critical Temp. (deg F)	Estimated Wind (mph)
1	3	-0.63	-24.65	880	797	1000	80	5.00	NG	5.50	194	169	5.90
2	35	0.25	8.44	1024	1040	1000	80	5.00	??	5.50	198	206	5.46
3	85	0.39	15.25	1042	1073	1000	80	5.00	??	5.50	214	230	4.15

Test Back Close

Figure 2-15 Span Summary Dialog Box for the Line Rating Software

The columns in the span summary dialog box are described below:

<u>Back Structure Number</u> – Identifies the structure at start of the span

<u>Clearance Margin</u> – Provides the amount of excess clearance that remains at the most restrictive point in the span. This will usually be different than the monitor clearance margin described below because it is often not practical to place the sagometer at the point of most restrictive clearance. Thus, in most cases the clearance margin will be a calculated value.

<u>Temperature Margin</u> – Temperature change which will make the clearance margin equal to zero.

<u>Amps Available</u> – Estimated current at which the clearance margin will become zero.

<u>Emergency Amps Available</u> – Emergency operation current which will make the clearance margin zero after a user designated time interval.

<u>Amps Used</u> – Measured value of current flow.

<u>Ambient Temperature</u> – Measured ambient temperature at span location.

<u>Solar Radiation</u> – Measured solar radiation at span location.

<u>Click For Details</u> – Clicking on this column brings up the Span Info Dialog Box described below.

<u>Monitor Clearance Margin</u> – Measured value of clearance margin at instrument site. Program could also be set up to receive sag or clearance to ground if the instrument cannot measure clearance margin.

<u>Equivalent Wire Temperature</u> – Calculated wire temperature that will match the monitor clearance margin.

Critical Wire Temperature – Calculated wire temperature at which the clearance margin becomes zero. This temperature is used in the calculation of the Amps available column.

Estimated Wind – A calculated estimate for the wind blowing on the span. This value is used in the calculation of the critical temperature and hence the amps available. We decided it would be better to calculate an effective wind than to attempt to measure it for the following reasons:

- Would need to measure both wind speed and direction relative to span
- Wind speed and direction can change quickly making measurements at planned sampling period (10 minutes?) nearly meaningless.
- Wind may vary significantly throughout the span.

2.3.1.3. Span Info Dialog Box:

This span info dialog box, shown in Figure 2-16, displays graphical information for a single span. The current span configuration is displayed in a profile view, 3d view, plan view and a camera view. Clicking on the profile, 3d or plan views brings up a full screen view in which the user can pan around and measure distances. Data in this box is updated real time as data is received from instruments.

Clicking the "Back" button returns to the Span Summary Dialog Box and camera view will only be displayed if monitoring equipment is capable of supplying the image. The example above includes optional aerial photo in plan view and structure detail in profile view. This level of detail might not be available in all PLS-CADD models.

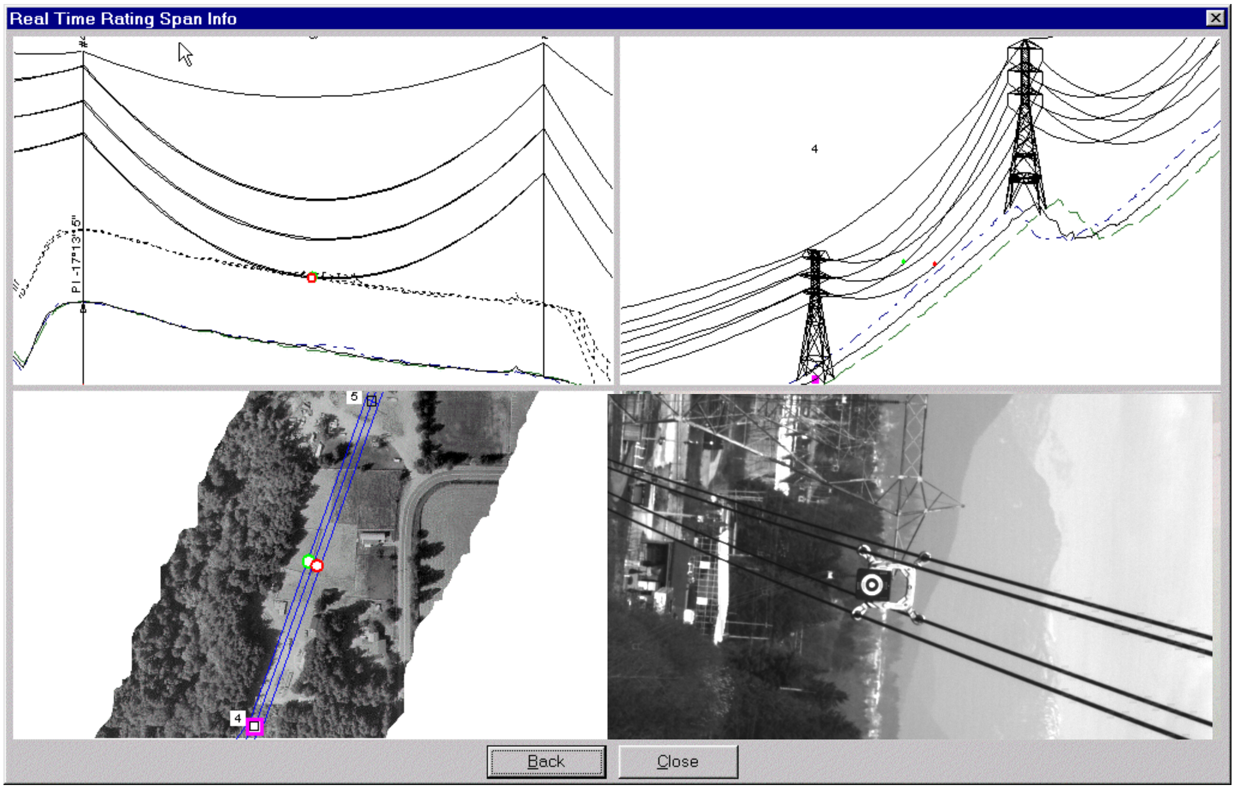


Figure 2-16 Span Info Dialog Box for the Line Rating Software

2.3.1.4. Span Monitoring Configuration Dialog Box:

The span monitoring configuration dialog box is shown in Figure 2-17 and is used to tell the program which spans are to be selected for real time monitoring and to establish a link between these spans and the instruments reporting data on the spans.

Span Monitoring Configuration

	Back Structure Number	Set Number and Description	Cable Name	Include Span	Has Monitor	Monitor Name	Distance to Target (ft)	Phase Number
1	1	1	guinea	N	N			1
2	1	2 LC	linnet	N	N			1
3	1	3 RC	linnet	N	N			1
4	2	1	guinea	N	N			1
5	2	2 LC	linnet	Y	N	span3left		3
6	2	3 RC	linnet	N	N			1
7	3	1	guinea	N	N			1
8	3	2 LC	linnet	Y	Y	span3left	150	3
9	3	3 RC	linnet	N	N			
10	4	1	guinea	N	N			1
11	4	2 LC	linnet	N	N			1
12	4	3 RC	linnet	N	N			1
13	5	1	guinea	N	N			1
14	5	2 LC	linnet	N	N			1
15	5	3 RC	linnet	N	N			1
16	6	1	guinea	N	N			1
17	6	2 LC	linnet	N	N			1
18	6	3 RC	linnet	N	N			1
19	7	1	guinea	N	N			1
20	7	2 LC	linnet	N	N			1
21	7	3 RC	linnet	N	N			1
22	8	1	guinea	N	N			1
23	8	2 LC	linnet	N	N			1
24	8	3 RC	linnet	N	N			1
25	9	1	guinea	N	N			1
26	9	2 LC	linnet	N	N			1
27	9	3 RC	linnet	N	N			1
28	10	1	guinea	N	N			1
29	10	2 LC	linnet	N	N			1

OK Cancel

Figure 2-17 Span Monitoring Configuration Dialog Box for the Line Rating Software

Columns in the span monitoring configuration dialog box are:

Back Structure Number – Identifies structure at start of span

Set Number And Description – Identifies the attachment point on the structure. Description is set by user when the structure is built. In the example above set "1" is the shield wire, "2 LC" is the left circuit and "3 RC" is the right circuit.

Wire Name – Name of the wire attached at this location.

Include Span – Should the span be included in the set of spans for real time rating. It may not always be practical to put a sagometer in the most critical span so the program will allow inclusion of spans that do not include a sagometer. Row #5 shows a span which is included despite not having a sagometer. This span will be evaluated using information from sagometer span3left which is located in the next span.

Has Monitor – Does the span contain a sagometer.

Monitor Name – Used to determine which monitor will drive the calculations used for checking clearances in this span. The monitor could be located in this span but could also be located in a different span.

<u>Distance To Target</u> – Horizontal distance from attachment at back structure to sagometer target. Tells the program where in the span the sagometer measurements are being taken.

<u>Phase Number</u> – Each attachment set can have up to three phases. This field specifies which of the three phases is to be included for real time rating.

2.3.1.5. Alarm Configuration Dialog Box:

The alarm configuration dialog box, shown in Figure 2-18, allows the user to enable/disable a number of different alarms and associate a sound effect with each alarm.

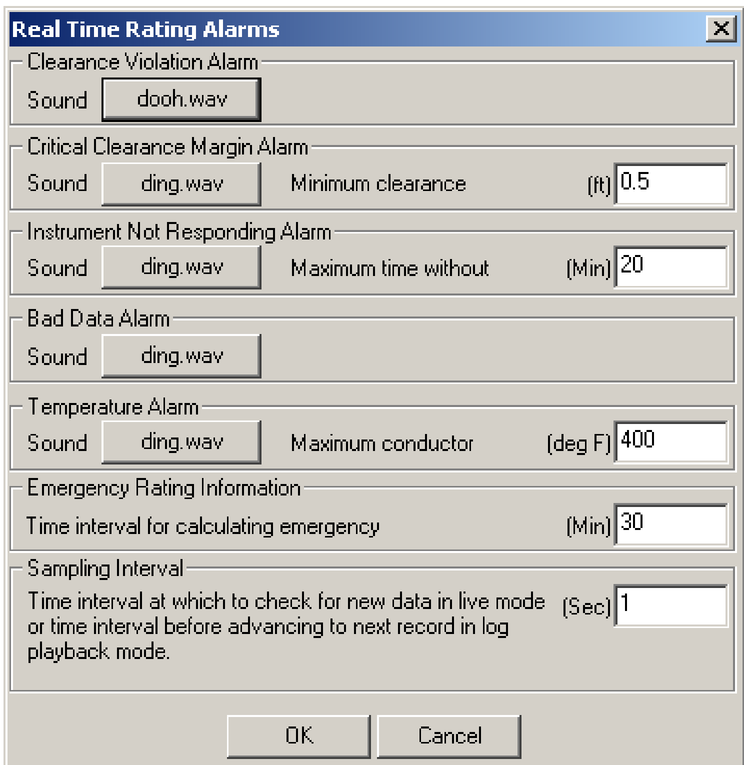


Figure 2-18 Alarm Configuration Dialog Box for the Line Rating Software

<u>Clearance Violation Alarm</u> – Triggered when one or more spans have a clearance margin less than or equal to zero.

<u>Critical Clearance Margin Remaining</u> – Triggered when one or more spans have a clearance margin less than the selected value.

<u>Instrument Not Responding Alarm</u> – Triggered when no data received from an instrument over a user set time limit.

<u>Bad Data Alarm</u> – Triggered when the data received from the instrument can't be reconciled with the PLS-CADD model. For example: PLS-CADD calculates a conductor temperature of 80 degrees from the instrument sag margin but the ambient temperature reported by the instrument is higher than 80 degrees.

Temperature Alarm – Triggered when the conductor temperature exceeds the specified temperature.

Emergency Rating Information – Time interval for calculating emergency rating

Sampling Interval – Time interval to sample data from a live sensor or log file

2.3.2. Acceptance Testing of Line Rating Software

The acceptance testing of the line rating software was to determine whether it functions as specified and required for practical use in performing line rating calculations. The acceptance testing of software was decided to be conducted as part of the field trial of the prototype system. A complete software acceptance test plan is provided in Appendix B.

The line rating software is developed around Power Line System's existing PLS-CADD software program. The PLS-CADD software program has proven itself to be a stable and accurate tool for transmission line design. Because the PLS-CADD software has been thoroughly tested and has a proven track record, testing of its core line modeling functionality was not necessary and was not conducted as part of the line rating software testing. The acceptance testing will include verification of the following line rating functionality:

- Ability of the software to accurately display the correct location(s) of monitors within the span(s)
- Ability of the software to read log data files and "live" data files
- Ability of the software to accurately calculate line rating values given the data file information
- Ability of the software to accurately display the clearances at monitor locations and at monitored spans based on clearance values provided in the line rating tables
- Ability of the software to accurately calculate emergency ratings for user-specified time limit
- Ability of the software to trigger alarms and indicators when appropriate
- Ability of the software to accurately save and restore line rating information

2.4. Prototype System Trial Use and Refinement

The plan for the prototype system trial use consisted of the installation and operation of the prototype system at a California utility. The goal for the trial use was to test the sensor and software under field setting, to evaluate the real-time rating function of the system and the features of the system designed to facilitate studies to re-rate existing lines. The test plan consisted of the following:

- Sagometer Sensor installation – Install a complete Sagometer system with ancillary weather sensors (pyranometer, temperature probe and anemometer). Adjust and calibrate the Sagometer with the assistance of a survey crew. Verify on site that the Sagometer and all the weather sensors are functioning properly and their data are being recorded properly. Verify that the power supply is functioning properly and the cellular transceiver is registered on the cellular network. Once all subsystems have been tested contact the sensor system through the cellular network while still on site. One day following installation download data stored over the past evening to verify proper operation of the clearance sensor during nighttime conditions.

- Software Installation – The line rating software package is installed on a "Host PC" provided by the utility. The software package consists of two "components":
  - Software that retrieves the data from the sensor system, combines that data with the utility provided line load data and passes the combined data to the PLS-CADD/Line Rating Module
  - PLS-CADD/Line Rating Module

  The data retrieval software is installed and tested independent of installing and/or operating the PLS-CADD/Line Rating Module software. Once both components are installed and tested the Host PC is ready to receive data from the sensor package and the utility loading data.

3.0 Project Outcomes

Trial Use at Southern California Edison

Southern California Edison (SCE) volunteered their facilities for the trial use of the prototype line rating system. A four-span line section near the Rosemead SCE offices was chosen as the test section. The location and orientation of the test line are shown in Figure 3-1. The system was installed on October 1, 2002 with the help of a two-man line crew using an insulator washing truck. The system was installed in approximately 6 hours with the line energized. A survey crew provided assistance with placement of the target and calibration of the system. Figure 3-2 shows the installed sensor system along with the ancillary weather instruments. The installation of the sensor system and its components met or exceeded all test plan criteria.

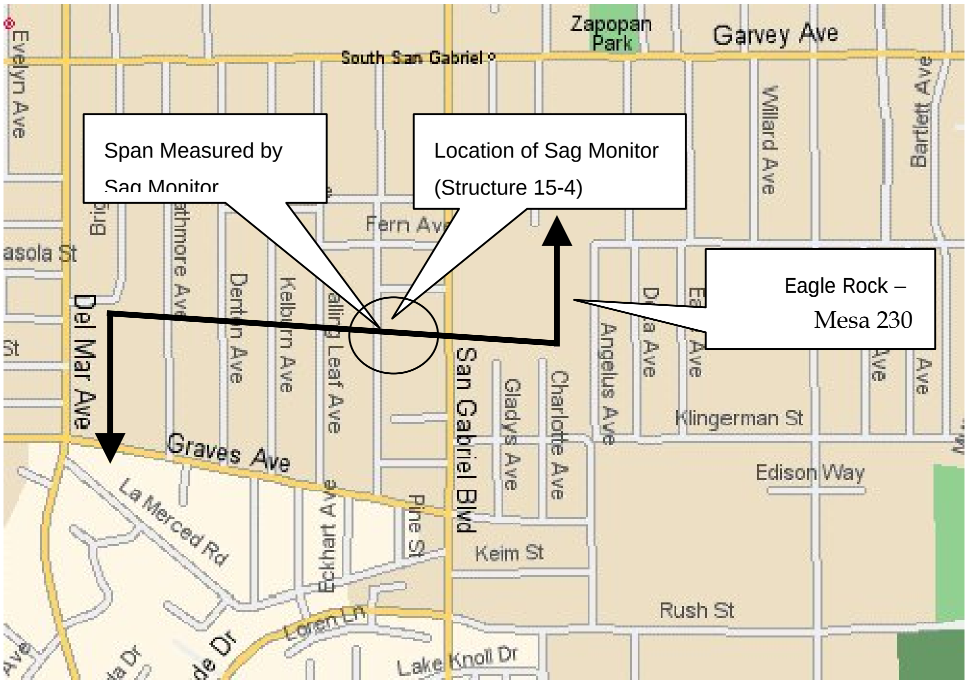


Figure 3-1 Location of the Selected Test Span from Southern California Edison System

Data from the Sagometer system for the week of October 11 - 15, 2002 is shown in Figure 3-3 and Figure 3-4. In Figure 3-3, the clearance at the target is plotted along with the horizontal displacement of the conductor at the target and the correlation, a relative value relayed by the Sagometer sensor relating the confidence the sensor has in the measurement. Figure 3-4 plots the clearance at the target along with temperature and solar radiation.

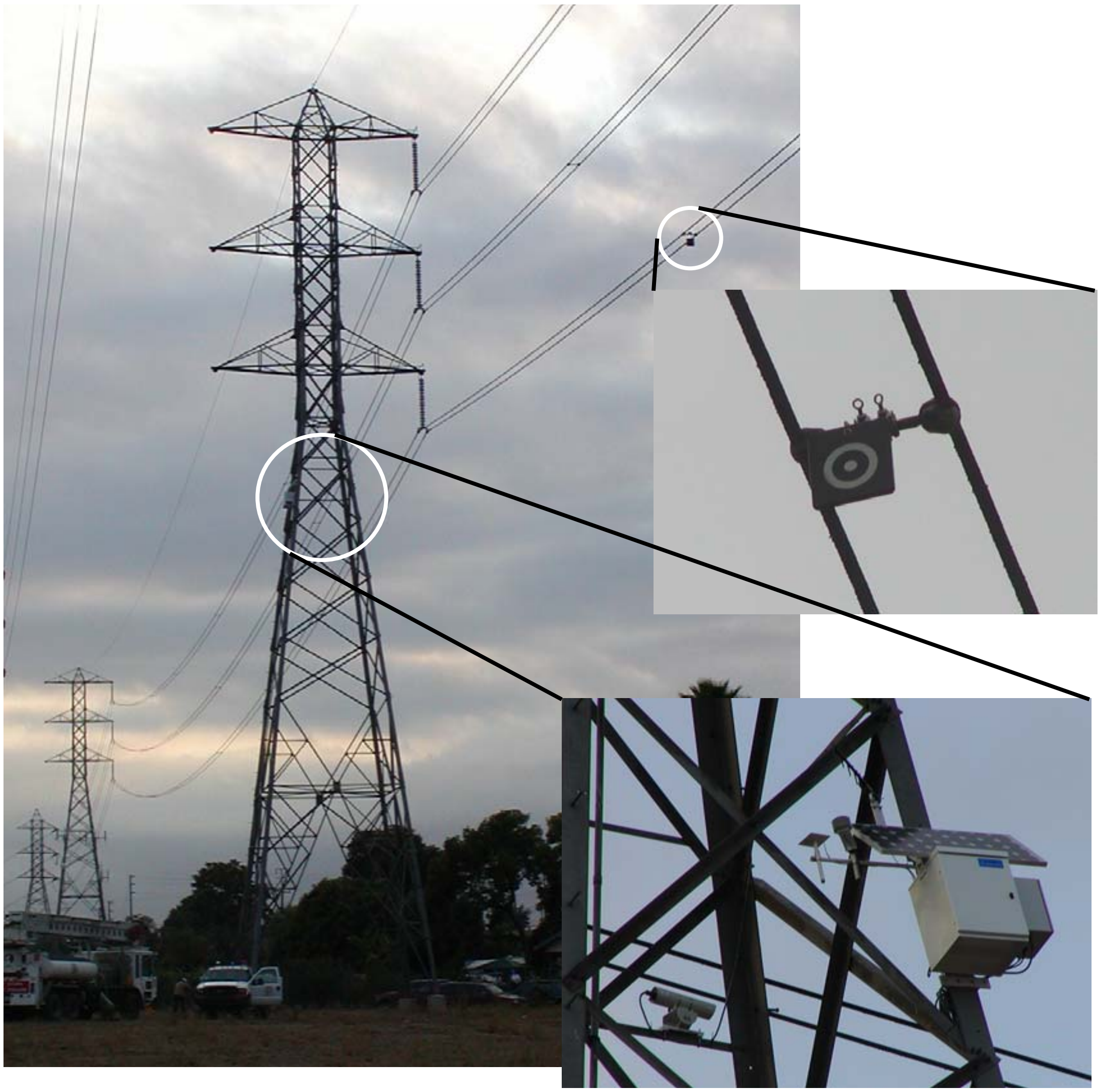


Figure 3-2 Prototype Sagometer System Installed at Line From Southern California Edison's System

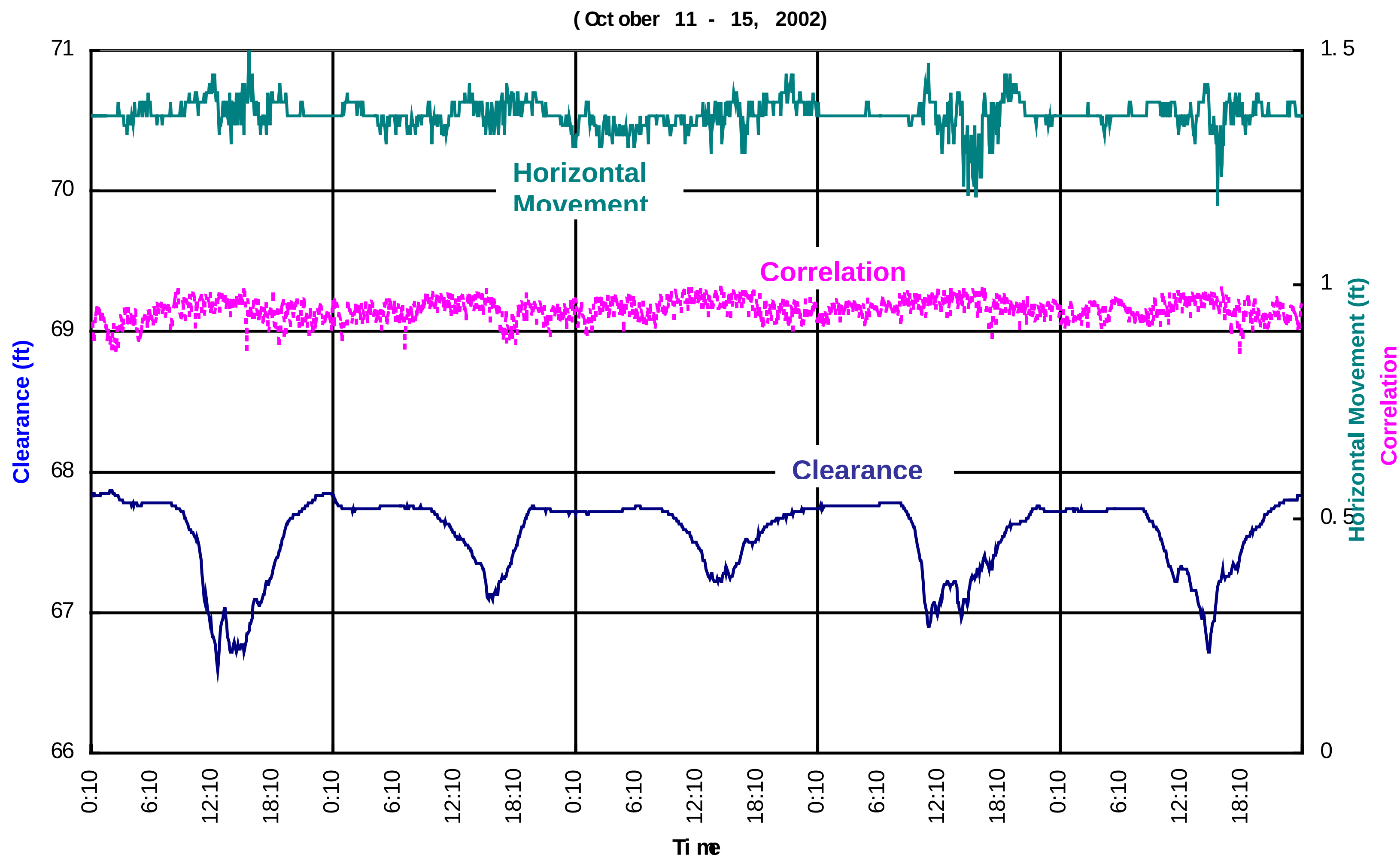


Figure 3-3 Sagometer Data for a Typical Week in October

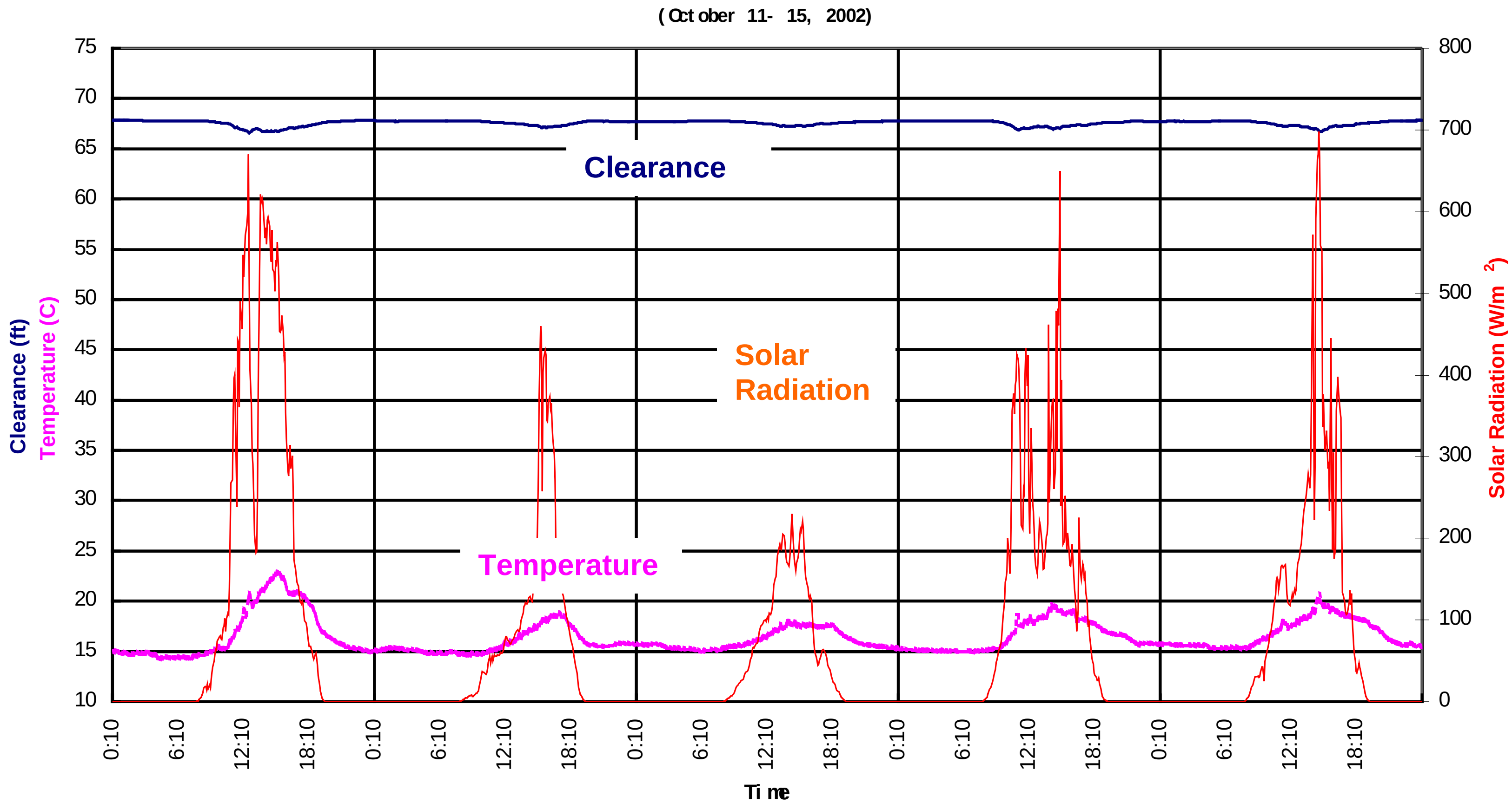


Figure 3-4 Ground Clearance Plotted Against Weather Data for a Typical Week in October

SCE created a PLS-CADD line model of the line section monitored. Figure 3-5 contains a screen capture showing the line model as displayed in PLS-CADD. The target is shown as a red circle 150 feet to the right of structure number 3.

CDPD (Cellular Digital Packet Data) was chosen as the communication option as data would be available on a real-time basis and an internet connection would likely be easily available for the Host PC. Upon installation of the line rating software on the Host PC it was discovered that the SCE local area network (LAN) configuration created a conflict with the data collection software. This prohibited the software from communicating and retrieving data from the Sagometer system. This was primarily because of the SCE LAN configuration and could be resolved by involving the IT people at SCE. However, because of the time constraints it was not feasible to resolve this issue in a timely manner. Thus a real-time operation of the line rating software with the sensor data could not be performed at the host PC installed at SCE.

As an alternative to real-time operation the sensor and line load data were retrieved and combined by EDM. The combined data were tested with the line model in the Line Rating Module to ensure the validity of the data. The data were then provided to SCE for use in the line rating software and conduct software acceptance testing. Software acceptance testing was conducted at SCE per the acceptance testing plan described in Appendix B. The software passed the acceptance testing. However, a few minor bugs and possible improvements were identified for the module. These improvements will be incorporated in the next release of the software.

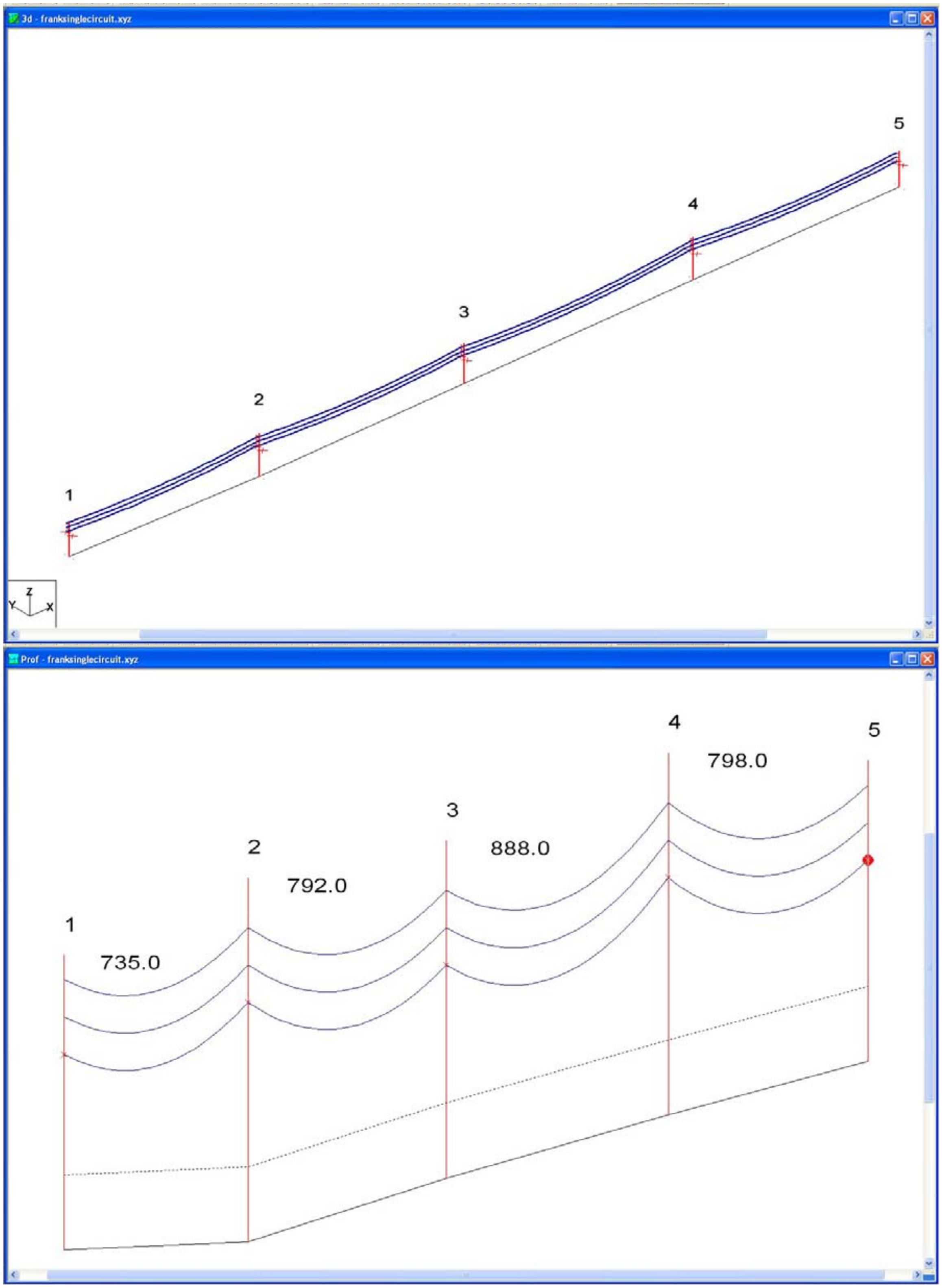


Figure 3-5 PLS-CADD Model of Southern California Edison Test Span

4.0 Conclusions And Recommendations

4.1. Conclusions

The PIER project was successful in developing real-time sensors for ground clearance/sag measurements and rating software to provide real-time capacity for the monitored lines. Two sensor systems, a pulsed laser based (LDM) system and a machine vision based (Sagometer) system, were developed and tested. The developed sensor system met or exceeded the performance standards set for the project. Prototype Sagometer sensor was fabricated and field tested on a line in Southern California Edison's system. The Sagometer system is designed to integrate with EPRI's Dynamic Thermal Circuit Rating software. In addition, a real-time rating software module was developed around an existing sophisticated computer program (PLS-CADD) developed by Power Line Systems, Inc. (PLS) which enables the three-dimensional modeling of overhead lines and terrain for the purposes of designing new lines. The use of the PLS-CADD as the basis for the line rating module allows for monitoring of clearance/sag in any of the critical spans based on clearance/sag data from the span in which the Sagometer is installed. The rating module provides a steady state rating for the line along with an emergency rating for user defined time period. The rating software can provide real-time rating based on either a clearance limit or a thermal limit.

- The developed sensors can measure power-line clearances over a range of 20 to 100 feet with an accuracy of better than $\pm$ 2 inches. In fact, the resolution for the Sagometer sensor is 0.25 inch.
- The developed sensors are capable of real-time monitoring and dynamic rating of lines. In addition, historical clearance data gathered using these sensors could also be used for rating studies.
- Field installation of the sensor system can be completed and commissioned (debugged) in less than 4 hours. The Sagometer sensor system is designed to be installed without the need of taking an outage and the only component that gets attached to the live conductor is a completely passive target.
- The monitoring system is capable of reliable, low-maintenance operation (1 - 2 maintenance visits per year in conjunction with a utility's routine line patrol/inspection activities) in an outdoor environment. Approximately twenty second generation Sagometer systems have now been installed at several utilities under EPRI sponsored Tailored Collaboration (TC) projects for over one year. These systems have not required any maintenance over that time period except for minor communication issues that were more due to the telecommunication providers system related issues.
- The monitoring system is capable of operation in remote sites during daylight and at night.
- The monitoring system is capable of reliable operation in temperatures ranging from –10°F to +120°F.
- The monitoring system is capable of ready integration of additional devices to the sensor system for making ancillary measurements such as wind speed and ambient temperature.

- The monitoring system is capable of autonomous remote reboot of hardware in the event of an operational or environmental anomaly that causes proper operation to cease. The data logger monitors data coming in from the Sagometer sensor and reboots the sensor if no data has been available for a set duration of time.

4.2. Economic Benefits and Benefits to California

Development of a real-time rating system provides several energy efficiency, cost, labor and environmental benefits for California. These benefits are listed below and are based on our discussions with people in the industry.

- A 2-5 percent increase in the power transfer capabilities of the existing grid.
- A 20-30 percent improvement in the transmission efficiency of existing lines that are limited by ground clearances.
- A 15-25 percent reduction in the need for acquisition and construction of additional ROW's and the associated environmental impacts.
- An improvement in system reliability enabled by improved knowledge of line capacity under normal and emergency conditions.
- Deferral of capital expenditures of $150-200 million for the construction of new transmission lines in the next 10 years.
- Long-term or permanent deferral of capital expenditures of $70-90 million per year for reconductoring projects.
- Short-term deferral of capital expenditures of $8-12 million per year for reconductoring projects.
- Creation of one to four jobs at each California utility with overhead lines with capacities limited by ground clearances.
- Elimination of the energy consumption associated with the manufacturing and installation of the components that would be utilized in constructing the new lines that would be needed in the absence of the proposed technology.
- Elimination of the atmospheric pollutants resulting from the manufacturing and installation of the components that would be used in constructing the new transmission lines that would be needed in the absence of the proposed technology.
- Elimination of the use of the non-renewable resources associated with the manufacturing of the components needed for constructing the new lines that would be needed in the absence of the proposed technology.
- Stabilization or reduction in electricity rates enabled by more efficient use of existing overhead facilities and deferral of capital expenditures for the construction of new facilities.

4.3. Commercialization Potential

Both the developed sensor systems and rating software have excellent commercialization potential. The Sagometer sensor and line rating software are both ready for commercialization. Because this project has been running in parallel with other EPRI sponsored projects, multiple Sagometer systems have been deployed at utilities across USA and Canada as part of EPRI

Tailored Collaboration projects for long term performance evaluation. The LDM sensor also has commercialization potential but its packaging requires further development.

4.4. Recommendations

The following recommendations are offered to further enhance the real-time rating capabilities and to make it widely acceptable by utilities:

- Further evaluation of the Sagometer sensor system on lines in California is needed to demonstrate the capabilities of the developed sensor system and to make it acceptable for dynamic rating of lines. This will help familiarize the California utilities with the system and also help identify any California utility specific needs for integration.
- Develop a line rating kit that incorporates a complete set of tools (sensors, analytical procedures, and software) for studying the behavior of transmission lines under "real-world" operating conditions for a relatively short period thereby enabling optimization of static ratings. This tool could be used as a study tool and be moved from one line to another with relative ease.
- Conduct line behavior research and develop procedures/guidelines for deploying sensor technology to optimize ratings for individual lines, paths, groups of lines, systems. Understanding the behavior of lines, paths and systems will help identify the critical lines that need to be monitored in order to obtain optimized ratings for the entire system.
- Develop procedures and guidelines for "seamless" real-time rating data integration into control room. For rating data to be used in real-time it needs to be integrated into the utilities control room and California Independent Systems Operator's (CAISO) control room.
- Perform economic benefit analysis studies of using real-time rating technology to quantify the benefits of using these new sensor technologies.
- Further develop the packaging for the pulsed laser based (LDM) sensor to enable it to be offered as an alternative sensor to the Sagometer. The LDM sensor could be beneficial in certain situations. One of the advantages of the LDM sensor is that it does not require any field calibration and provides a direct and accurate measurement of ground clearance.

5.0 References

"Feasibility of Using Various Sensor Technologies for Ground Clearance and/or Conductor Tension Monitoring." EPRI report prepared by EDM International Inc., Southwest Research Institute and Colorado State University, April 1998.

"Development and Demonstration of a Functional PSTM Unit." EPRI report prepared by EDM International Inc. and Southwest Research Institute, November 1998.

"Dynamic Rating Concepts for Overhead Lines." EPRI Report prepared by EDM International Inc., November 2000.

Appendix A

Functional Specifications for Sensor System

Operational Specifications

Conductor clearance to ground measurement range	15 to 100 ft

(Note: This specification only applies to the sensors that will be mounted on the conductor and directly measure the distance between the conductor and the ground or a target thereon. This range limitation does not apply to the PSTM sensor. The PSTM sensor performs a direct measurement of sag, which can be translated to a clearance.)

Minimum clearance measurement accuracy	±2 inches for sensors located at any point on the conductor span
Installation	Must be able to be installed on a live line in less than six hours utilizing a two-man bucket truck, from a tower with hot-sticks, or helicopter.
Optional ancillary measurements	Must be able to support optional ancillary measurements including: • Ambient temperature • Conductor temperature • Solar radiation • Wind velocity and direction • Amperage
Data acquisition rate	Periodic acquisition rate up to one measurement per minute
Data transmission options	Periodic and/or on-command transmission

Sensor attachment requirement (Note: Each of the three sensor systems that are the subject of the R&D effort has different attachment requirements. The list of requirements encompasses the requirements of the three different sensor systems.)	Attach to live conductor Attach to a tower in the line to be monitored or a fixed structure adjacent to the line being monitored and have an unobstructed line of sight to the conductor to be monitored. Attachment hardware should not damage the conductor or degrade its performance in any way.
Sensor target requirement	May or may not need a target on the conductor or on the ground. If a target is required on the conductor it shall be capable of being installed with the conductor energized.
System reboot/reset	System shall have the capability to automatically reboot in the event of a transient operational anomaly and to be remotely or locally rebooted/reset on command.
Conductor	Must be functional on single or bundled conductors of aluminum, copper, or steel. *Optional* - Attachment hardware should be cushioned for installation on ACSS conductor.

Environmental Specifications

Operating temperature range	-10º F to 122º F (-23º C to 50º C)
Optional extended temperature range	-10º F to 145º F (-23º C to 63º C)
Storage temperature range	-40º F to 158º F (-40º C to 70º C)
Humidity range	Up to 95% relative humidity (non-condensing)
Operational weather conditions	• Rain (1/2 inch per hour or less) • Moderate snow (1 inch per hour or less) • Operate in winds up to 40 mph • Withstand winds up to 115 mph
Operational lighting conditions	Ambient light during daylight and at night (The PSTM-based approach will require illumination of the target for nighttime operation. However, the target will not appear visible from the ground.)
Operational vibration conditions	Normal wind induced line vibration
Operational electromagnetic field	Must operate in electromagnetic steady state and transient fields produced by power lines at distances within 6 inches of the conductor and operate at system voltages from 12 kV to 550 kV.

Electrical Power Specifications

Sensors mounted on conductors	Inductive power obtained from lines carrying between 100 and 4000 amps
Sensors mounted on line towers or other fixed structures	The components of the system that are attached to a tower or other fixed structure shall be capable of being powered using either of the following:
	AC power from distribution line
	Power from solar cells
Optimization of sensor power demands	Incorporate “sleep mode” between measurements

Communication Specifications

Communication links	Telephone & Cell Phone
(Note: The requirements for these links encompass those for both transmitting data from a conductor mounted sensor to a field data logging and communication system and from the system to a distant site, e.g. an office or operations center computer.)	Analog (Standard) Digital (Optional – will be only explored) Satellite (Satellite communication option will be only explored but no equipment will be purchased) Radio Radio frequency or infrared link capable of transmitting information up to 1000 feet between conductor mounted sensor and field data logging and communication system
Data transfer format	Either Binary or ASCII
Integration with SCADA systems	System shall be compatible with the most commonly used SCADA protocol MODBUS ASCII / Binary, or DNP 3.0, or UCA, or Other
Field data logging and communication system	Located on tower or other fixed structure

Appendix B

Line Rating Software Acceptance Test Plan

This document outlines the testing procedures that the line rating software will undergo to determine whether it functions as specified and required for practical use in performing line rating calculations. Specifically this document covers the following issues:

- Testing location, equipment and participants
- Description of the specific functionality that will be tested
- Reporting documents for use by test participants

The purpose of the software acceptance testing is to identify bugs in the program and/or potential enhancements to the program. Bugs found during the testing will be corrected by the project team. Additionally, participants are welcome to provide comments regarding desired additional features or enhancements to the software. All bugs and suggested enhancements should be noted on the provided log sheets and submitted to EDM at the conclusion of the testing.

Testing Location, Equipment and Participants

The line rating software acceptance testing will take place at the individual test participant's location. The Commission Contract Manager will select the test participants with input from the project team. The test participants shall be technical personnel with knowledge of line rating concepts and grid operations and working knowledge of the PLS-Cadd software. The test participants shall be selected from the project team's technical personnel (not the software developers), TAG members or technical personnel associated with the TAG members, or others with the ability to provide valuable input during the acceptance testing phase. Each participant shall perform at least four hours of testing.

The participants will use their own hardware to perform the testing. EDM will provide a prototype version of the software program to each of the participants along with other necessary materials such as instructions, test data files and reporting documents.

Specific Functionality to Be Tested

The line rating software is developed around Power Line System's existing PLS-Cadd software program. The PLS-Cadd software program has proven itself to be a stable and accurate tool for transmission line design. Because the PLS-Cadd software has been thoroughly tested and has a proven track record, testing of its core line modeling functionality will not be necessary as part of this project and will not be conducted as part of the line rating software testing. The acceptance testing will include verification of the following line rating functionality:

- Ability of the software to accurately display the correct location(s) of monitors within the span(s)
- Ability of the software to read log data files and "live" data files

- Ability of the software to accurately calculate line rating values given the data file information
- Ability of the software to accurately display the clearances at monitor locations and at monitored spans based on clearance values provided in the line rating tables
- Ability of the software to accurately calculate emergency ratings for user-specified time limit
- Ability of the software to trigger alarms and indicators when appropriate
- Ability of the software to accurately save and restore line rating information

In addition to the above testing requirements, participants are asked to comment on the logic and flow of the program as well as verify that all necessary variables are present to perform line rating calculations.

Opening the Line Model Files

EDM will provide the participants with two different line models to be used for the testing. One of the models will be a small, simple model that will be used to test the majority of the line rating functionality of the software. By using a simple model, the participants will be able to more easily verify the basic functionality of the program and identify any bugs that may be present. Another more sophisticated model will be provided that the participants will use to evaluate the overall flow and performance of the line rating features of the software using a more realistic situation. This portion of the testing will be less structured than that using the simple model, allowing the participants to "play around" with the software while noting any anomalies or desired enhancements. While this is a less structured phase of the testing program, the participants should also verify that the basic functionality that was tested using the simple model also performs as expected when using the more complex model.

Participants should experiment with opening, saving and reopening both of the line model files throughout the testing and note any problems encountered. For example, participants may want to close and save the files at various stages of the testing and then open them and ensure that all of the information was restored properly.

Configuring Spans for Monitoring

The first step in setting up a line for monitoring/rating in the line rating software is to configure the spans that will be included, or monitored. To test the functionality of this portion of the software, the participants should open the Span Monitoring Configuration dialog box and set up at least 5 different scenarios of monitor configurations, ensuring that all views of the line model accurately reflect each of the configurations entered in the dialog box.

Once the participants have determined that the locations of the monitors and monitored spans are being accurately represented in all of the views, they will be asked to enter names of log files, provided by EDM, for each of the monitors. The information in the log files will be such that running these will test the majority of the functionality of the software. For example, the log files will contain data created to cause clearance violations to the ground profile and/or aerial obstacles in order to test the functionality of the alarms.

Running the Program Using Log Files

EDM will provide a specific set of instructions to the participants describing what to look for while running the log files. The participants will step through the log files one entry at a time verifying that the performance of the software matches the expected performance for each of the records. This portion of the testing will verify the ability of the program to accurately display the clearances in all of the views, to accurately trigger alarms and indicators at the appropriate times, and to update the emergency amps allowed based on the user-defined time limit for emergency operation.

During this phase, test participants are asked to perform line rating calculations for a few of the log file records to verify the accuracy of the ratings calculated by the line rating software.

Running the Program Using “Live” Files

Because it is not practical to configure all of the test participants with the ability to truly read live data files, EDM will provide the ability to read simulated live files to test this portion of the software functionality. EDM will supply a program that will generate numbers and feed them to the “live” file. Because the majority of the functionality in the line rating software is the same whether reading log files or live files, simulating the live file portion of the testing rather than truly reading live data should be adequate for acceptance testing.